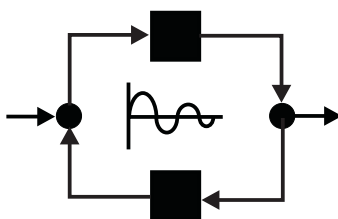




The International Congress for global Science and Technology



**ICGST International Journal on Automatic
Control & System Engineering
(ACSE)**

**Volume (9), Issue (II)
December, 2009**

**www.icgst.com
www.icgst-amc.com
www.icgst-ees.com**

© ICGST LLC, Delaware, USA, 2009

ACSE Journal
ISSN: Print 1687-4811
ISSN Online 1687-482X
ISSN CD-ROM 1687-4838
© ICGST LLC, Delaware, USA, 2009

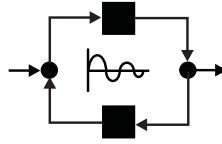
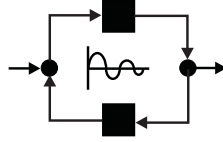


Table of Contents

Papers	Pages
P1110843436, R. Ebrahimi and M.A. Vali and M. Samavat and A.A. Gharavisi “A COMPUTATIONAL METHOD FOR SOLVING OPTIMAL CONTROL OF SINGULAR SYSTEMS USING THE LEGENDRE WAVELETS”	1--6
P1110838373, C.BOUCHOUCHA and M.N. MANSOURI and F. MIMOUNI “Protection Strategy and Robustness of Maghreb Electrical System: An Analytical Study”	7-- 14
P1110909663, Tlili saber and Mibar hassen, “Robust Control for a Class of Nonlinear Systems”	15-- 22
P1110917728, A. Errahmani and M. Benyakhlef and I. Boumhidi, “Greenhouse Model Identification based on Fuzzy Clustering Approach”	23--27
P1110850016, HONG-ZHEN ZHENG and DIAN-HUI CHU and DE-CHEN ZHAN and XIAO-FEI XU, “Modeling and Approach for Vendor Managed Inventory Cyclic IRP”	29--34
P1110924771, A. Errahmani and M. Benyakhlef and I. Boumhidi, “Decentralized Fuzzy Control Applied to a Greenhouse”	35--40
P1110943904, Ashraf Mohamed Hemeida, “Improvement of Voltage stability and Critical Clearing Time for Multi- machine Power Systems Using Static VAR Compensator”	41--47
P1110937868, M. Sundaram and P. Navaneethan and M. Vasanthakumar, “Magnetic Analysis and Comparison of Switched Reluctance Motor with Different Stator Pole Shapes Using a 3D Finite Element Method”	49--53



**ICGST International Journal on Automatic Control & System Engineering -
(ACSE)**

**A publication of the International Congress for global Science and Technology -
(ICGST)**

ICGST Editor in Chief: Dr. Ashraf Aboshosha

www.icgst.com, www.icgst-amc.com, www.icgst-ees.com

editor@icgst.com



A COMPUTATIONAL METHOD FOR SOLVING OPTIMAL CONTROL OF SINGULAR SYSTEMS USING THE LEGENDRE WAVELETS

R. Ebrahimi¹, M.A. Vali², M. Samavat¹, A.A. Gharavisi¹

1. Department of Electrical Engineering, Shahid Bahonar University

2. Department of mathematics, Shahid Bahonar University

Kerman, IRAN

Ebrahimi_123ali@yahoo.com, mvali@mail.uk.ac.ir, msamavat@mail.uk.ac.ir, a_gharaveisi@yahoo.com

Abstract

By the use of elegant operational properties of Legendre wavelets, a direct computational algorithm for evaluation the optimal control and trajectory of linear singular systems with a quadratic cost functional is developed. The state variable, state- rate, and the control vector are expanded in Legendre orthonormal basis with unknown coefficient. The technique is straightforward and very convenient for computer programming. An illustrative example is given to demonstrate the applicability of the proposed method.

Keywords: Optimal control; singular systems; Legendre wavelets; operational matrix; orthogonal functions

1. Introduction

Wavelet theory is relatively new and is an emerging area in mathematical research. In recent years, wavelets have found their way into different fields of science and engineering. Wavelets permit the accurate representation of a variety of functions and operators. Orthogonal functions and polynomial series have been received considerable attention in dealing with various problems of dynamical systems. The main characteristic of this technique is that it reduces these problems to those of solving a system of algebraic equations, thus greatly simplifying the problems. The approach in [1] is based on converting the underlying differential equation into integral equations through integration, approximating various signals involved in the equation by orthogonal series and using the operational matrix of integration, to eliminate the integral operations. Special attention has been given to application of the Legendre wavelets [2], the linear Legendre wavelets [1], and the cosine and sine (CAS) wavelets which are used to solve Fredholm integral equation in [3]. Recently, constrained optimal control problems had been discussed many authors [4,5,6], the advantage of using Legendre wavelets as compared to the other wavelets is that in the present method the operational matrix are zeros, and integration

of the product of two Legendre wavelet function vectors is an identity matrix, hence making Legendre wavelets computationally very attractive. Singular systems, also commonly called generalized or descriptor systems in the literature appear in many practical situations including engineering systems, economic systems, network analysis, and biological systems (see e.g. [7, 8, 9]). In fact, many systems in the real life are singular in nature. They are usually simplified as or approximated by non-singular models because there is still lacking of efficient tools to tackle problems related to such systems. The structural analysis of linear singular systems, using either algebraic or geometric approach, has attracted considerable attention from many researchers during the last three decades (see e.g. [10, 11, 12, 13, 14, 15, 16, and 17] and the references cited therein). Generally speaking, almost all the research works dealing with singular systems are the natural extension of those results for non-singular counterparts, although it is much harder in obtaining solutions associated with singular systems. In this paper we extend the Legendre wavelets technique to study the problem of optimal control of linear singular systems with quadratic performance. The state variable $x(t)$, state rate $\dot{x}(t)$ and control variable $u(t)$ are expanded by Legendre wavelets with unknown coefficients. The advantage of this method is that we can choose series numbers willfully.

Also the properties of Legendre wavelets are used to relate the unknown coefficients of $\dot{x}(t)$ to the coefficients of $x(t)$. Using this method the dynamics of the systems are converted to a system of algebraic equations. The necessary conditions of optimality are imposed to solve the quadratic programming by using the Lagrange multipliers.

The reminder of the paper is organized as follows: section (2) is about the preliminaries and problem statement; section (3) focuses on the main result, section (4) demonstrate a benchmark example. Finally section (5) is the conclusion.



2. Preliminaries and Problem Statement

2.1 Properties of the Legendre wavelets

2.1.1 Multiresolution of analysis (MRA)

In recent years, wavelets have found their way into many different fields of science and engineering. Wavelets constitute a family of functions constructed from dilation and translation of single function called the mother wavelet. When the dilation parameter a and the translation parameter b vary continuously, we have the following family of continuous wavelets [18].

$$\psi_{ab}(t) = |a|^{-\frac{1}{2}} \psi\left(\frac{t-b}{a}\right), \quad a, b \in R, \quad a \neq 0$$

If we restrict the parameters a and b to discrete values as $a = 2^{-k}$, $b = n2^{-k}$, then

$$\psi_{kn}(t) = 2^{\frac{k}{2}} \psi(2^k t - n)$$

form an orthogonal basis. MRA has been used to construct the wavelets. We need the following definition: the increasing sequence $\{V_j\}_{j \in \mathbb{Z}}$ of subset of $L^2(R)$ with scaling function ϕ is called MRA if it satisfies the condition

- (i) $\cup_j V_j$ Is dense in $L^2(R)$,
- (ii) $\cap_j V_j = \{0\}$,
- (iii) $f(t) \in V_j \Leftrightarrow f(2^{-j}t) \in V_0$,
- (iv) $\{\phi(t-n)\}_{n \in \mathbb{Z}}$ Is an orthogonal basis for V_0 .

Using the definition of MRA, the quence $\{2^{\frac{j}{2}} \phi(2^j t - n)\}_{n \in \mathbb{Z}}$ forms an orthonormal basis for V_j .

Let $\psi(t)$ be the mother wavelet, then we have [19]

$$\psi(t) = \sum_{n \in \mathbb{Z}} a(n) \phi(2t - n)$$

and by suitable conditions, the sequence $\{2^{\frac{k}{2}} \psi(2^k t - n)\}_{k, n \in \mathbb{Z}}$ forms an orthonormal basis for $L^2(R)$.

Legendre wavelets $\psi_{m,n}(t) = \psi(k, n, m, t)$ have four arguments; $k = 1, 2, 3, \dots$, $\hat{n} = 2n - 1$, $n = 1, 2, 3, \dots, 2^{k-1}$, m is the order for Legendre polynomials and t is the normalized time. They are defined on interval $[0, 1)$ by:

$$\psi_{m,n}(t) = \begin{cases} (m + \frac{1}{2})^{\frac{1}{2}} 2^{\frac{k}{2}} L_m(2^k t - \hat{n}), & \frac{\hat{n}-1}{2^k} \leq t < \frac{\hat{n}+1}{2^k}, \\ 0 & \text{otherwise} \end{cases}$$

(1)

Where $m = 0, 1, 2, \dots, M-1$, $n = 1, 2, 3, \dots, 2^{k-1}$. In Eq.

(1), the coefficient $(m + \frac{1}{2})^{\frac{1}{2}}$ is for orthonormality.

Here, $L_m(t)$ are the well-known Legendre polynomials of order m which are orthogonal with respect to the weight function $w(t) = 1$ and satisfy the following recursive formula:

$$L_0(t) = 1, L_1(t) = t,$$

$$L_{m+1}(t) = \left(\frac{2m+1}{m+1}\right)tL_m(t) - \left(\frac{m}{m+1}\right)L_{m-1}(t), m = 1, 2, 3, \dots$$

2.1.2. Function approximation

Suppose a signal $f(t)$ has finite energy over the interval $[0, 1)$. Then $f(t)$ can be represented by Legendre wavelets as follows

$$f(t) = \sum_{n=1}^{\infty} \sum_{m=0}^{\infty} c_{n,m} \psi_{n,m}(t), \quad (2)$$

Where $c_{n,m} = (f(t), \psi_{n,m}(t))$ in which $(,)$ denotes the inner product.

If the infinite series in Eq. (2) is truncated, then Eq. (2) can be written as

$$f(t) \approx \sum_{n=1}^{2^{k-1}} \sum_{m=0}^{M-1} c_{n,m} \psi_{n,m}(t) = C^T \Psi(t), \quad (3)$$

Where C and $\Psi(t)$ are $2^{k-1}M \times 1$ matrices given by

$$C = [c_{10}, c_{11}, \dots, c_{1M-1}, c_{20}, \dots, c_{2M-1}, \dots, c_{2^{k-1}0}, \dots, c_{2^{k-1}M-1}]^T$$

$$\Psi(t) = [\psi_{10}(t), \psi_{11}(t), \dots, \psi_{1M-1}(t), \psi_{20}(t), \dots, \psi_{2M-1}(t), \dots, \psi_{2^{k-1}0}(t), \dots, \psi_{2^{k-1}M-1}(t)]^T \quad (4)$$

The integration of the vector $\Psi(t)$ defined in Eq. (4) can be obtained as

$$\int_0^t \Psi(t') dt' = P \Psi(t), \quad (5)$$

Where P is the $(2^{k-1}M) \times (2^{k-1}M)$ operational matrix for integration as

$$P = \frac{1}{2^k} \begin{bmatrix} L & H & H & \dots & H \\ 0 & L & H & \dots & H \\ \vdots & 0 & \ddots & \ddots & \\ & & & & H \\ 0 & 0 & \dots & 0 & L \end{bmatrix} \quad (6)$$

In Eq. (6) H and L are $M \times M$ matrices given by



$$H = \begin{bmatrix} 2 & 0 & \dots & 0 \\ 0 & 0 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 0 \end{bmatrix}$$

And

$$L = \frac{1}{2^k} \begin{bmatrix} 1 & \frac{1}{\sqrt{3}} & 0 & 0 & \dots & 0 & 0 \\ \frac{\sqrt{3}}{3} & 0 & \frac{\sqrt{3}}{3\sqrt{5}} & 0 & \dots & 0 & 0 \\ 0 & \frac{\sqrt{5}}{5\sqrt{3}} & 0 & \frac{\sqrt{5}}{5\sqrt{7}} & \dots & 0 & 0 \\ 0 & 0 & \frac{\sqrt{7}}{7\sqrt{5}} & 0 & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \dots & 0 & \frac{\sqrt{2M-3}}{(2M-3)\sqrt{2M-1}} \\ 0 & 0 & 0 & 0 & \dots & \frac{-\sqrt{2M-1}}{(2M-1)\sqrt{2M-3}} & 0 \end{bmatrix}$$

The integration of product of two Legendre wavelets vector function is obtained as:

$$D = I = \int_0^1 \Psi(t) \Psi^T(t) dt, \quad (7)$$

Where I is an identity matrix.

2.2 Problem statement

Consider linear time invariant (LTI) singular system

$$E\dot{x}(t) = Ax(t) + Bu(t) \quad (8)$$

$$x(0) = x_0 \quad (9)$$

Where $x \in R^p$ is the state of the system, $u \in R^z$ is the input vector of the system, $E \in R^{p \times p}$ is assumed to be singular with $0 < \text{rank}(E) < p$, and A, B are real constant matrices of appropriate size. The problem is to find the optimal control $u(t)$ and the corresponding state trajectory $x(t)$, $0 \leq t \leq L$, satisfying equation (8) and (9) while minimizing the cost function

$$J = \frac{1}{2} x^T(L) S x(L) + \frac{1}{2} \int_0^L [x^T(t) Q x(t) + u^T(t) R u(t)] dt \quad (10)$$

In equation (10), T denotes transposition, S, Q and R are matrices of appropriate dimensions, S and Q are symmetric positive semi-definite matrices and R is a symmetric positive definite matrix.

3. Main result

3.1. Approximation of the singular system

By expanding $x_N(t)$, $u_Z(t)$ and $\dot{x}_N(t)$ in Legendre wavelet functions, we determine the following approximated values, i.e. for $N = 1, 2, 3, \dots, n$, and $Z = 1, 2, 3, \dots, z$ we get

$$x_N(t) = A_N^T \Psi(t) \quad (11)$$

$$u_Z(t) = U_Z^T \Psi(t) \quad (12)$$

$$\dot{x}_N(t) = C_N^T \Psi(t) \quad (13)$$

Where

$$A_N = [a_{N10}, a_{N11}, \dots, a_{N1M-1}, a_{N20}, \dots, a_{N2M-1}, \dots, a_{N2^{k-1}0}, \dots, a_{N2^{k-1}M-1}]^T \quad (14)$$

$$U_Z = [u_{Z10}, u_{Z11}, \dots, u_{Z1M-1}, u_{Z20}, \dots, u_{Z2M-1}, \dots, u_{Z2^{k-1}0}, \dots, u_{Z2^{k-1}M-1}]^T \quad (15)$$

$$C_N = [c_{N10}, c_{N11}, \dots, c_{N1M-1}, c_{N20}, \dots, c_{N2M-1}, \dots, c_{N2^{k-1}0}, \dots, c_{N2^{k-1}M-1}]^T \quad (16)$$

Where $\{a_{Nij}\}$, $\{u_{Zij}\}$ and $\{c_{Nij}\}$ are unknown.

$$i = 1, 2, 3, \dots, 2^{k-1}, j = 1, 2, 3, \dots, M-1$$

Let

$$(Ax(t))_N = Y_N^T \Psi(t) \quad (17)$$

$$(Bu(t))_N = L_N^T \Psi(t) \quad (18)$$

$$(Ex(t))_N = W_N^T \Psi(t) \quad (19)$$

Using equation (17)-(19) for each $N, N = 1, 2, 3, \dots, n$ the equation (8) has the form

$$W_N^T \Psi(t) = (Y_N^T + L_N^T) \Psi(t)$$

By equating the coefficients of the same-order Legendre wavelets, we obtain for $N = 1, 2, 3, \dots, n$ and

$$W_N^T = (Y_N^T + L_N^T) \quad (20)$$

Also, we can have

$$x(t) = \int_0^t \dot{x}(t') dt' + x(0)$$

$$A_N^T \Psi(t) = C_N^T P \Psi(t) + K_N^T \Psi(t)$$

Equivalently

$$A_N^T - C_N^T P - K_N^T = 0 \quad (21)$$

$$K_N = [x(0), 0, \dots, 0 | x(0), 0, \dots, 0 | \dots | x(0), 0, \dots, 0]^T$$

We define

$$F_{NS} = a_{NS} - \sum_{r=1}^{2^{k-1}M} c_{Nr} P_{rS} - K_{NS} \quad (22)$$

$$N = 1, 2, \dots, n, \quad S = 1, 2, \dots, 2^{k-1}M$$

3.2. The performance index approximation

We now approximate the performance index J by using Legendre wavelets.

Let

$$\alpha = \begin{pmatrix} (a_{10} \ a_{11} \ \dots \ a_{1M-1} \ a_{20} \ \dots \ a_{2M-1} \ \dots \ a_{2^{k-1}0} \ \dots \ a_{2^{k-1}M-1})^T \\ \vdots \\ (a_{N10} \ a_{N11} \ \dots \ a_{N1M-1} \ a_{N20} \ \dots \ a_{N2M-1} \ \dots \ a_{N2^{k-1}0} \ \dots \ a_{N2^{k-1}M-1})^T \end{pmatrix} \quad (23)$$



$$\beta = \begin{pmatrix} (u_{110} \ u_{111} \ \dots \ u_{11M-1} \ u_{120} \ \dots \ u_{12M-1} \ \dots \ u_{12^{k-1}0} \ \dots \ u_{12^{k-1}M-1})^T \\ \vdots \\ (u_{Z10} \ u_{Z11} \ \dots \ u_{Z1M-1} \ u_{Z20} \ \dots \ u_{Z2M-1} \ \dots \ u_{Z2^{k-1}0} \ \dots \ u_{Z2^{k-1}M-1})^T \end{pmatrix} \quad (24)$$

$$\hat{\Psi}_1(t) = \begin{pmatrix} \Psi^T(t) & & \\ & \ddots & \\ & & \Psi^T(t) \end{pmatrix} \hat{\Psi}_2(t) = \begin{pmatrix} \Psi^T(t) & & \\ & \ddots & \\ & & \Psi^T(t) \end{pmatrix} \quad (25)$$

Note that α, β and $\hat{\Psi}_1(t)$ and $\hat{\Psi}_2(t)$ are matrices of order $N2^{k-1}M \times 1, Z2^{k-1}M \times 1$ and $N \times N2^{k-1}M$ and $Z \times Z2^{k-1}M$ respectively. Using equation (11) and (12) and (23) - (25) the state and control vector can be expressed as

$$x(t) = \hat{\Psi}_1(t)\alpha \quad (26)$$

$$u(t) = \hat{\Psi}_2(t)\beta \quad (27)$$

Substituting equation (26) and (27) in equation (10) we get

$$\begin{aligned} J &= \frac{1}{2} \alpha^T \hat{\Psi}_1^T(1) S \hat{\Psi}_1(1) \alpha \\ &+ \frac{1}{2} \alpha^T \left[\int_0^1 \hat{\Psi}_1^T(t) Q \hat{\Psi}_1(t) dt \right] \alpha \\ &+ \frac{1}{2} \beta^T \left[\int_0^1 \hat{\Psi}_2^T(t) R \hat{\Psi}_2(t) dt \right] \beta \end{aligned} \quad (28)$$

Equation (28) can be computed more efficiently by using equation (7) and writhing as

$$\begin{aligned} J &= \frac{1}{2} \alpha^T [\Psi(1)\Psi^T(1) \otimes S] \alpha + \frac{1}{2} \alpha^T (D \otimes Q) \alpha \\ &+ \frac{1}{2} \beta^T (D \otimes R) \beta \end{aligned} \quad (29)$$

Where $\otimes$ denotes the kronecker product [20]

Remark: As it is shown in (29) the dynamic cost function is converted to a statistic cost function and it simplifies the problem considerably.

3.3. Solution of the optimization problem

The optimal control problem has been reduced to a parameter optimization problem which can be stated as follows. Find α and β so that $J(\alpha, \beta)$ is minimized subject to the constraints in equations (20) - (22)

Let

$$L = J + \sum_{N=1}^n \sum_{S=1}^{2^{k-1}M} \lambda_{NS} F_{NS} \quad (30)$$

Where $\lambda_{NS}, N=1,2,\dots,n, S=1,2,\dots,2^{k-1}M$ are unknown Lagrange multipliers. Then the necessary conditions for extremum are

$$\begin{cases} \frac{\partial L}{\partial \alpha_{NS}} = 0 \\ \frac{\partial L}{\partial \beta_{ZS}} = 0 \end{cases} \quad N=1,2,\dots,n \quad Z=1,2,\dots,z, \quad (31)$$

$$S=1,2,\dots,2^{k-1}M,$$

$$\frac{\partial L}{\partial \lambda_{NS}} = 0 \quad (32)$$

Remark: As it shown in (6) the operational matrix P has so many zeros and this fact results in a considerably saving of computing time.

4. Illustrative example

Consider the linear singular system [21]

$$\begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u \quad (33)$$

$$X(0) = \begin{bmatrix} 1 \\ \frac{\sqrt{2}}{2} \end{bmatrix} \quad (34)$$

With the cost function

$$J = \frac{1}{2} \int_0^2 [X^T(\tau) X(\tau) + U^2(\tau)] d\tau \quad (35)$$

The problem is to find the optimal control $u(t)$ which minimizes equation (35) subject to (33) and (34).

To obtain the Legendre wavelets approximations, we first covert the interval $[0,2]$ to $[0,1]$ by means of the

transformation $t = \frac{\tau}{2}$. We determine Legendre wavelets

approximations for $M=5, k=2$,

Let

$$\begin{aligned} A_1 &= [a_{110} \ a_{111} \ a_{112} \ a_{113} \ a_{114} \ a_{120} \ a_{121} \ a_{122} \ a_{123} \ a_{124}]^T \\ A_2 &= [a_{210} \ a_{211} \ a_{212} \ a_{213} \ a_{214} \ a_{220} \ a_{221} \ a_{222} \ a_{223} \ a_{224}]^T \end{aligned}$$

$$U = [u_{10} \ u_{11} \ u_{12} \ u_{13} \ u_{14} \ u_{20} \ u_{21} \ u_{22} \ u_{23} \ u_{24}]^T$$

$$C_1 = [c_{110} \ c_{111} \ c_{112} \ c_{113} \ c_{114} \ c_{120} \ c_{121} \ c_{122} \ c_{123} \ c_{124}]^T$$

$$C_2 = [c_{210} \ c_{211} \ c_{212} \ c_{213} \ c_{214} \ c_{220} \ c_{221} \ c_{222} \ c_{223} \ c_{224}]^T$$

Applying equations (28), we obtain the following approximation for J

$$\min J = \sum_{n=1}^2 \sum_{m=0}^4 a_{1nm}^2 + a_{2nm}^2 + u_{nm}^2$$

Using equations (30) and (31) the Legendre wavelets approximation for $x_1(t)$ and $u(t)$ can be calculated.

In table I and II, a comparison is made between the exact solution and approximated values of $x_1(t)$ and $u(t)$ using present method for $M=5, k=2$, and the exact solution.

5. Conclusion

The Legendre wavelets and the associated matrix of integration (operational matrix) are applied to solve the optimal control of singular systems. The method is based upon reducing a linear singular quadratic optimization problem to a set of algebraic equations. The integration of the product of two Legendre wavelet function vectors is an identity matrix, hence making Legendre wavelets computationally very attractive. Illustrative example is included to demonstrate the validity and applicability of the technique.



6. Acknowledgements

The authors wish to express their sincere thanks to the referee for valuable suggestions which improved the final manuscript.

table I . Estimated and exact value of $x_1(t)$

Solution number	Time	$x_1(t)$		
		Exact solution	Legendre wavelets	Error
1	0.0	1.0000	1.0012	0.0012
2	0.1	0.7536	0.7536	0.0000
3	0.2	0.5680	0.5671	0.0009
4	0.3	0.4280	0.4273	0.0007
5	0.4	0.3226	0.3225	0.0001
6	0.5	0.2431	0.2446	0.0015
7	0.6	0.1832	0.1832	0.0000
8	0.7	0.1381	0.1379	0.0002
9	0.8	0.1041	0.1039	0.0002
10	0.9	0.0784	0.0784	0.0000
11	1.0	0.0591	0.0595	0.0004

table II . Estimated and exact value of $u(t)$

Solution number	Time	$u(t)$		
		Exact solution	Legendre wavelets	Error
1	0.0	0.7071	0.7079	0.0008
2	0.1	0.5329	0.5328	0.0001
3	0.2	0.4016	0.4010	0.0006
4	0.3	0.3027	0.3021	0.0006
5	0.4	0.2281	0.2280	0.0001
6	0.5	0.1719	0.1729	0.0010
7	0.6	0.1296	0.1296	0.0000
8	0.7	0.0976	0.0975	0.0001
9	0.8	0.0736	0.0735	0.0001
10	0.9	0.0555	0.0554	0.0001
11	1.0	0.0418	0.0420	0.0002

7. References

- [1] F.Khellat, S. A. Yousefi. The linear Legendre mother wavelets operational matrix of integration and its application. J.Franklin Institute, 343(2006)181-190.
- [2] M.Razzaghi, S. Yousefi, The Legendre wavelets operational matrix of integration. Int. J. Syst. Sci. 32(4) (2001)495-502.
- [3] S. Yousefi. A. Banifatemi, Numerical solution of Fredholm integral equations by using CAS wavelets. Applied Mathematics and Computation(2006),doi: 10.1016/j.amc.2006.05.081.
- [4] M.Razzaghi, S. Yousefi, Legendre wavelets method constrained optimal control problems. Math. Meth. Appl. Sci. (2002) 25:529-539
- [5] R. Ebrahimi, M. Samavat, M.A.Vali and A.A. Gharavisi, APPLICATION OF FOURIER SERIES DIRECT METHOD TO THE OPTIMAL CONTROL OF SINGULAR SYSTEMS, International Journal on Automatic Control and System Engineering (ACSE), Volum(7), Issue(II), Pages(19-24), November,2007
- [6] R. Ebrahimi, M. Samavat, M.A.Vali and A.A. Gharavisi, FOURIER SERIES AND OPTIMAL CONTROL OF SINGULAR SYSTEMS, 38 Th Mathematical Conference of Iran, University of Zanjan, (2007).
- [7] L. Dai, singular control system, Springer, Berlin, 1989
- [8] M. Kuijper, First Order Representation of Linear systems, Birkhauser, Boston, 1994.
- [9] F. L. Lewis, A survey of linear singular systems, Circuits, Systems Signal Process. 5 (1) (1986) 3-36.
- [10] P. V. Dooren, The eigenstructure of an arbitrary polynomial matrix:computational aspects, Linear Algebra Appl. 50 (1983) 545-579.
- [11] P. V. Dooren, The generalized eigenstructure problem in linear systems theory, IEEE Trans. Automat. Control 26 (1981) 111-129.
- [12] T. Geerts, Invariant subspaces and invertibility properties for singular systems: the general case, Linear Algebra Appl. 183(1993) 61-68
- [13] J. J. Loiseau, Some geometric considerations about the Kronecker normal form, Internat. J. control 42 (1985) 1411-1413.
- [14] A. G. J. MacFarlane, N. Karcianas, Poles and Zeros of linear multivariable systems: a survey of the algebraic, geometric and complex variable theory, Internat. J. Control 24 (1976) 33-74.
- [15] P. Misra, P. V. Dooren, A. Varga, computation of structural invariants of generalized state-space systems, Automatica 30 (1994) 1921-1936.
- [16] G. Verghese, Infinite frequency behaviour in generalized dynamical systems, Ph. D. Dissertation, Stanford University, 1978.
- [17] Z. Zhou, M. A. Shayman, T. J. Tarn, Singular systems: a new approach in the time domain, IEEE Trans. Automat. Control 32 (1) (1987) 42-50.
- [18] J.S.Gu, W. S. Jiang, The Haar wavelets operational matrix of integration, Int. J. Syst. Sci. 27 (1996) 623-628.
- [19] I. Daubechies, Ten Lectures on Wavelets, CBMS-NSF, 1992.
- [20] Lancaster P. Theory of Matrices. Academic Press: New York, 1969.
- [21] Balachandran K, Murugesan K. optimal control of singular system via single-term Walsh series. International Journal of computer Mathematics 1992; 43: 153-159.





Ramazan Ebrahimi Ghari Abbas was born in Quochan Iran, 1981. He got his B.Sc, in electrical engineering 2005 from Mashhad University in Iran. Also he got his M.S.c, in electrical engineering 2007 from Bahonar university of Kerman.



M. Samavat got his B.Sc and M.Sc all in electrical engineering in 1982 and 1985 respectively from North Dakota state university in USA. Also he got his Ph.D in control engineering from Dept. of Automatic control and system engineering from university of Sheffield, England in Dec 2000.

Since 1985 he is a faculty member of electrical Dept in Bahonar university of Kerman. his research areas include stabilization, identification, model reduction and optimal control.



M. A. Vali got his B.Sc in pure mathematics in 1985 from Esfahan University in IRAN. he got his M.Sc in pure mathematics (Analysis) in Bahonar university of Kerman in 1987. Also he got his Ph.D in pure mathematics (optimal control) in 1999 from Bahonar university of Kerman in IRAN. Since 1987 he has been faculty member of Math Dep. Of Bahonar university of Kerman. his research areas include analysis, Linear algebra and optimal control.



Dr. Ali-Akbar Gharaveisi was born in Kermanshah, Iran, 1967. He received B.Sc., M.Sc., and PhD degrees from the Ferdowsi University of Mashhad, Mashhad, Iran, in 1990, 1995 and 2001 all in electrical engineering,

respectively. His field of knowledge and experience includes Control Systems, Power Systems Studies, Power Quality and Harmonic Mitigation, Electrical Machines and Drives.





Protection Strategy and Robustness of Maghreb Electrical System: An Analytical Study

C. BOUCHOUCHA*, M.N. MANSOURI **, F. MIMOUNI ***

* STEG, National Dispatching, **, *** ENIM Monastir,

(bouchoucha_chokri@yahoo.fr, cbouchoucha@steg.com.tn), mohamednejib.mansouri@enim.rnu.tn, Mfaouzi.Mimouni@enim.rnu.tn

Abstract

The major incidents are rare but their potential consequences can be very serious. The regional or national black out in the system causes the paralysis of the economic activity and an upheaval of the social life all the more marked as the breakdown is longer and wider. It is necessary for this reason to underline the correlation between the geographical extent of a black out zone and the duration of its realimentation, being given the specific difficulties of the reconstitution of a great system after collapse. In the case this occur, a plan of restoration of the network must be established beforehand. It is thus justified to make the provisions suitable to control the incidents when they happen, in order to limit the consequences in terms of extent, duration of the black out and to prepare a fast and effective realimentation for the affected consumers.

The approach of the majority of the electricity companies on these problems resulted in putting a whole of measurements called plan of defence, which based on the electrotechnical phenomena brought during incidents and their own dynamics. In this paper, we present the principle of defence plan design into preventive and curative action. Implementation of the defence plans integrating two groups of defensive measurements : local measurements of defence recommended generally for the lines of interconnection and centralized measurements of defence or co-ordinated called special protection system (SPS). A synthesis study of 111 centralized defence Plans made it possible to raise the strong and weak points of the whole of these defence plans. Finally the defence plans of the maghreb electrical system , as well as the encountered difficulties of implementation, were presented, commented and evaluated in order to create a new future optimal strategy.

Key words: collapse of the electrical system, strategy of defence, curative defence , preventive defence.

1. Introduction

The analysis of the continuity of service introduced the enumeration of standard states characterizing the operation of the high voltage electrical system. The disturbances affecting the system can result in more degraded states. The actions of defence make it possible to bring back the system to less degraded states.

To restore the state of the system primarily means to preserve the integrity of the network. This is to say: preserve as far as possible the maximum of network equipment and the interconnection grid system in service, to bring back the basic variables, the voltage, the frequency, the load of the connections in their respective limits, in order to avoid additional releases; but also to preserve and maintain available the manufacturing units, connected or not to the system. This restoration has a price: the shedding of load, the insolation of zones of the initial incident or victims of consecutive disturbances.

The defence measures ensure on the one hand the detection of abnormal situations and on the other hand the setting of automatic actions, generally preestablished, allowing to preserve the integrity of the network, under acceptable conditions of performance.

In the current state of the technique, and in accordance with the tradition in protection or adjustment, the establishment rests preferentially on local measurements and criteria, at least for the ultimate criterion of release of the countermeasure process. These conditions are indeed regarded the base of the robustness. A tendency today is to promote the use of systematic information coming from remote areas benefitting from the channels of information transfer high flow which furrow the networks.

For each mechanism, it is possible to define actions of defence, and for each one of them to draw up a list of the means likely to stop the development of the degradation process of the system's state. These means must be used in a radical way according to the process in which they fit. The design of the protection plans of such a network depends on the structure of the network topology, the site of production... etc. The paper is organized as follows; the 1st section after this introduction includes the design of the defense plans, the 2nd sections deals with the implementation of the defense plan. Section 3 includes the protection plan in the Maghreb electrical system. Section 4 states the improvement activities and the future recommendations. And finally the conclusion of the paper.



2. Design of defence in depth

At a major or generalized incident, various physical phenomena of degradation appear and follow one another. The safety of the system rests on the setting to be put a provisions of various nature, adapting to the dynamics of each phenomenon and preventing, detecting and treating the disfunctions being able to lead to their emergence and/or to control their evolution. These provisions are called lines of defence. The setting of the successive lines of defence constitutes the concept of defence in-depth (preventive and curative).

When a disturbance affects an element of network, the elementary system of protection starts, and if the network were in N-1 safety, its return towards a stable operation point is normally assured. So that an initially banal incident turns into a major incident, a series of dysfunctions must intervene such as a bad adjustment of protections, a refusal of opening breaker or that the point of initial operation does not guarantee a sufficient operation margin, etc.

The extension of the incident can also occur by various mechanisms directly affecting the state, the appearance of static instabilities, imbalance between production and consumption resulting from a parcelling out of the network, instabilities of voltage resulting from the absence of reserves or the automatic operation of tap changer of the distribution transformers, the inadequate load shedding, or the reaction speed of the operators unsuited to incident dynamics.

In any general information, the disturbances (causes) bring back the electric system from an initial state (F_0) to another state characterized by a operation point (F_1). The passage of the operation point from F_0 to F_1 is the transient state which gives place to fugitive primary effects. If the point of operation F_1 is unstable, the secondary effects appear as consequences of instabilities of the operation point. The following figure illustrates the transition from the system of a state F_0 to a state F_1 . A defence plan can act on the causes by preventive measure or on the effects by curative measure.

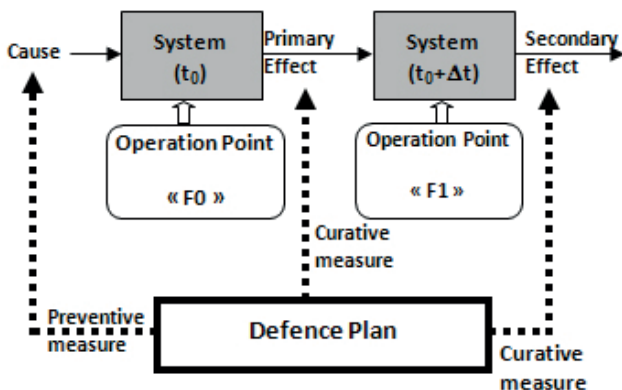


Figure 1: Possibility of action defence plan

2.1. Preventive defence: It consists into the actions carried out in order to avoid the starting of the collapse phenomena. The electric system must be insensitive to the consecutive losses of certain equipment following failures and/or risks considered to be probable and taken into account in the dimensioning of the system.

The carried out actions aim mainly:

- ✓ Preventive maintenance: to maintain the level of reliability, availability and performance of the



components to guarantee the service awaited and minimized the number of initiating events.

- ✓ To guarantee a quasi-absolute permanence of certain vital functions even in the event of failure of the equipment which fills them. This is obtained by the material and functional redundancy.

The reprogramming of the production constitutes the must securing task for the management of the electric system into preventive. The development of a new safe order moves the operation static point towards a state in which safety (N-1) and the operation margin are respected. This action is known as in closed loop since it controls the results.

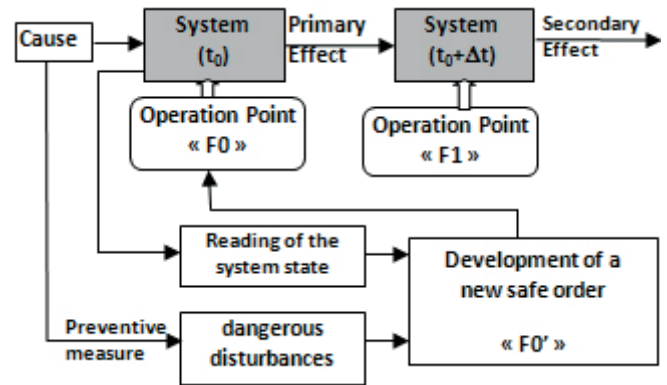


Figure 2: Preventive action in closed loop

2.2. Curative defence : this field gathers the whole of the automatic or manual actions which make it possible to detect the variations on certain sizes characteristic of the correct operation and to start the suitable corrective actions if necessary aiming at ensuring the protection of the materials and the safety of the system. The aim is above all to avoid the degeneration of incidents and/or failure in incident of great width. The counter measure adopted for these extreme situations is to disconnect from certain loads or certain zones particularly weakened in order to save the remainder.

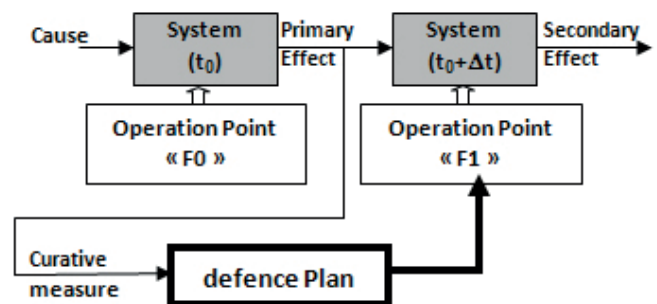


Figure 3: Curative action in open loop

There are 2 possibilities of curative action into curative, one based on the primary effects and the other on the side effects. However, the primary effects appeared in transient in the first moment and do not constitute a state of steady balance for the system. In the majority of the cases, these primary effects do not have consequences. Thus, they do not have direct impact on the safety of the electrical supply network and consequently they do not affect the customers. The action of such a plan based on the primary effects is known as in open loop.



The disadvantages of this plan lie mainly in:

- the difficulty in detecting the primary effects,
- calculation must be very fast,
- the risque of unnecessary operation: the primary effects may not have serious consequences (no appearance of side effects).

The primary effects, in certain cases and in the presence of the worsening factors, can excite the electric system to give rise to side effects. The action of a defence plan based on the side effects is known as in closed loop. The control of the results is based on the calculation of the operation point as shown in the following figure.

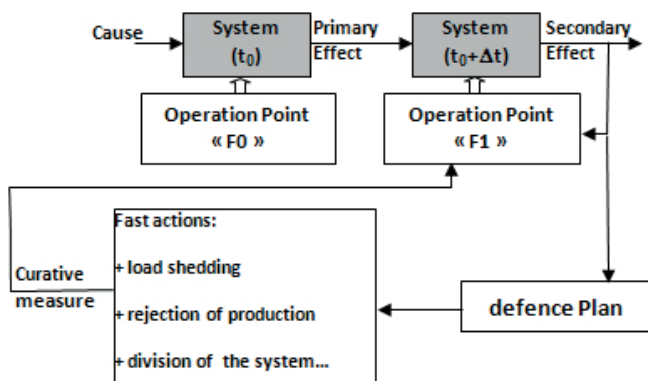


Figure 4: Curative action in closed loop

3. Implementation of the defence plans

The implementation of defence measures and the associated difficulties are exposed in this part while referring to the existing defence plan in the world integrating defence measures centralized and decentralized.

We distinguish two groups of defensive measures: local protections and traditional which are generally recommended for the lines of interconnection and centralized defence measures. The following paragraphs introduce these two groups.

3.1. Local measures of defence

The implementation of these measures requires detailed specifications taking into account the specificity of each country and the already implemented defence plans.

It is thus, to avoid the harmful consequences when a transmissible maximum is reached, it is recommended to equip each line with interconnection of the following protections: protection of maximum power, protection out of step and protection of under-frequency. The installation of a protection of low voltage is not recommended, it could involve inopportune releases at the time of the transitory angular excursions.

Protection of maximum power (maxP): The transmissible maximum power on an interconnection is the maximum capacity of exchange which can be exchanged between two zones without losing stability. Once this maximum is reached the system loses stability which results in a collapse of the voltage and/or a loss of synchronism. To avoid, in a preventive way, this type of break when a transmissible maximum is reached, a Watt-metric protection of maximum power (maxP) is necessary.



The adjustment of protection maxP must ensure a sufficient margin compared to the maximum power transmissible. The threshold maxP is regulated below the computed value of the transmissible maximum. To take into account the influence of the topological changes and the variations of the voltage, a margin of 20% compared to the calculated maximum transfer is generally recommended.

Out of step (maxθ): This protection must detect the conditions of loss of synchronism inter-zone or inter-area and separate them quickly. Its action is curative contrary to the protection maxP which has a preventive action (which acts before the transmissible maximum is reached). The protection usually used to detect the losses of synchronism is "out of step protection" which is based on a measure of the impedance seen on the line at the same time detects, in the plan (Resistance: R, reactance: X), if a preset zone is crossed. Protection is activated when this crossing was carried out in a time higher than a minimum. The publication "Modeling of out of step conditions in Power systems" presents the principles and of the examples of application.

Protection of under-frequency (minF): This protection ensures the separation of part of the load to restore in under network the balance Consommation/production. It limits the propagation of the frequency collapse from an area to another if a significant deficit of production is detected. The adjustment of this protection is generally located below a limited number of common thresholds solidarity (generally 2) between the various inter-connected parts.

3.2. Centralized defence plans

Coordinated measurements of defence are generally called special protection system (SPS). SPS is a protection system which was conceived to detect particular situations of the system which are known to cause an unusual stress of the system and which takes certain preset measurements to face the conditions observed in a controlled way. In certain cases, the SPS are conceived to detect operating conditions which were identified to cause an instability, an overload or a voltage collapse^[27].

A synthesis of the SPS based on a collection of approximately information from 49 companies of 17 different countries for a total of 111 SPS made it possible to raise the following strong and weak points of the these protection systems:

- ✓ The rejection of production and the load shedding are the most current measures followed in the SPS;
- ✓ The conditions of operating requiring the action of the SPS are not often met, but when it is the case, the SPS functions generally correctly;
- ✓ Much SPS at any moment requires to be in service;
- ✓ The alternatives which could be considered in the place of these SPS, are generally load shedding, the modification of the production and/or more restrictive operating condition. This last point means limitation of the capacities of transfer;
- ✓ The cost of a disfunction of the SPS is generally largely lower than the cost generated by the situations than the SPS makes can avoid. This implies that the installation of SPS is economically interesting and profitable, taking account of the disfunctions;



- ✓ All the existing SPS are solutions dedicated for particular systems. No supplier offers a complete solution covering the problems of data acquisition to the execution of the defence actions while passing by the design.

4. Defence Plan in the maghreb electrical system

In this paragraph we present the existing defence plans of the maghreb inter-connected networks (Morocco, Algeria, Tunisia and Libya) as well as the advantages and insufficiencies shown by simulations and of experience feedback. In addition we studied the real recording of the active transit at the level of the Interconnection Morocco-Spain (IME) following the release of a group in Morocco and the curve of corresponding simulation after a series of adjustment of dynamic parameters.

Releases of the Maghrebin interconnections during the 5 last years were presented. For the optimization of the loads to be lightened, works of simulation were started for a loss of production of 20%, 62%, 75 % and 80% of the peak power. The results show that a over shedding the two cases 62% and 75% of the load is recorded. However, the use of a criterion

$\frac{df}{dt}$ based on the rate of frequency variation for the criterion of load shedding is recommended to optimize the load to be lightened according to the variations of the system parameters as well as the dynamics of the disturbance (quantity lost according to time).

4.1 Adopted methodology of adjustments on installed protection of the maghreb defence plan

In the electrical supply networks with strong interconnection, three categories of state are retained:

- ✓ **Normal operation:** for which only actions of adjustment are taken (generally the frequency is in a beach of $\pm 200\text{mHz}$);
- ✓ **Operation in incident**, which implies the use of the principle of solidarity. The adjustment of the frequency generally rests on the control of the production (generally the frequency is in a beach of $\pm 1\text{Hz}$);
- ✓ **Operation in defence** which relates to states out of the usual criteria and implements average extremes like the automatic load shedding and the isolation of the thermal units with their auxiliaries.

In the case of network structures with simple interconnection, it is possible to establish a diagram of preventive shedding engaged simultaneously with the decoupling from the external network. Ideally, this initial shedding must be supplemented by a classical plan of shedding metric-frequency.

In order to adopt the provisions to take within the framework of the defence plan as well as the adjustments to make, studies of operation of the electrical supply networks are carried out in order to release the constraints of the system following the great disturbances. The constraints are of two types:

Static stresses: they are primarily the constraints of overload on the transport equipment or the voltage drops.

Dynamic stresses: these constraints are related to the dynamic behaviour of the electrical supply network to the disturbances which results in three phenomena:

- Voltage Collapse
- Collapse of frequency
- Loss of synchronism

The following figure shows the geographical diagram of the maghreb.

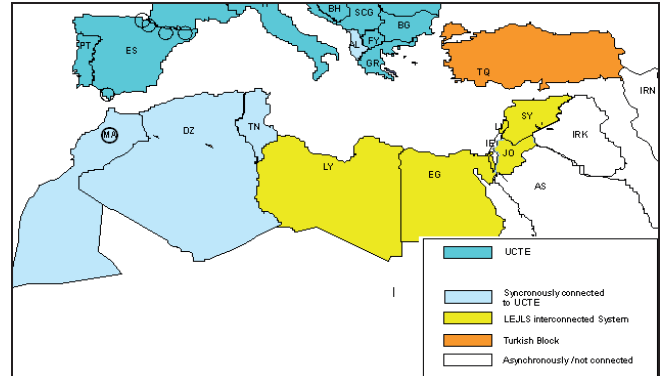


Figure 5: Geographical diagram of the maghreb

The operation studies of the maghreb network are carried out by the simulations with a function using the electric computation softwares requiring data bases of the various elements of the network (line, transformer, group... etc.). The dynamic behavior of the system depends on the response of the alternators and their systems of excitation and speed regulations, the parameters of the models used must be adjusted in order to obtain answers close to reality [28]

The approach adopted for this practical validation passed by the three 3rd following steps:

1. To analyze the history of the incidents in order to draw real facts of the lesson being able to explain the variations observed between reality and theory;
2. To make a study of sensitivity allowing to determine the most influential sizes following the loss of a group in an inter-connected system
3. To check on real incidents (of which the data are available) the validity of the conclusions drawn before. At the time of this third phase, the most influential parameters are adjusted until obtaining results nearest possible to recordings. From the various simulated incidents, it is then a question of drawing the most adequate models to the maghreb electric system.

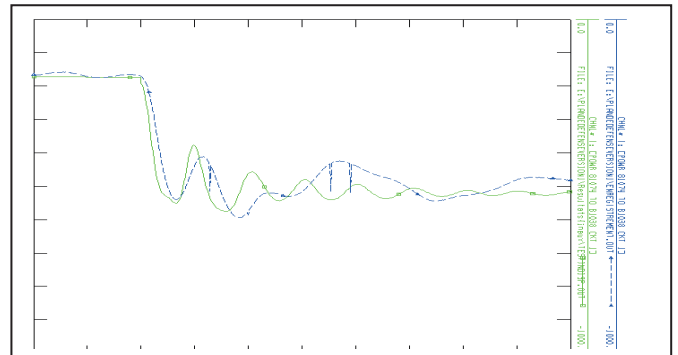


Figure 6 : adjustment between reality and simulation



As an indication, the following figure represents a real recording of the active transit on the level of the interconnection Morocco-Spain (IME) following the release of a group in Morocco and the curve obtained by simulation after a series of adjustments of the dynamic parameters.

4.2 Load shedding by minimum frequency (minF protection)

Because of the electrical interconnection between maghreb and Europe (UCTE) the load shedding by relay with minimum frequency in the maghreb countries will be requested only in the event of significant deficit of production and the separation of the concerned network or the networks from UCTE system.

In order to optimize the operation of the maghreb interconnections and to especially ensure a mutual help between the maghreb countries in disturbed mode, it was retained to adopt thresholds of load shedding to solidarity. This makes it possible to lighten the load on the whole of the maghreb countries inter-connected in order to adjust the consumption production balance and to preserve the maghreb interconnections and of the thresholds suitable for each network to safeguard the system in the event of deficit of production after the opening of these interconnections. The solidarity thresholds of load shedding and their lightened powers are as follows:

- ✓ Th1: $F1=49.3$ Hz: load shedding of 8% of the peak load .
- ✓ Th2: $F2= 49$ Hz: load shedding of 8% of the peak load.
- ✓ Th3: $F3= 48.7$ Hz: Opening of interconnections.

Below the $F3$ (frequency of network separation), some thresholds are integrated in order to safeguard the overdrawn network (objet of the initial disturbance). These thresholds are studied according to the size of the means of production installed and the time of launching equivalent to each network.

4.3 Load shedding controlled to the active transit on the interconnections and wattmetric defence plan (maxP)

All losses of production on the maghreb system is completely (96 to 98%) filled by the European network. The help of the European network comes through the cable Morocco-Spain, it crosses the maghreb networks to the overdrawn country. The request of the maghreb interconnections is all the more strong when the lost power is large. Defence Plans (by wattmetric protection and loss of synchronism) are installed on the lines of interconnection and have the function of opening the lines of interconnection and limiting the incident and its propagation from one network to the other. After the wattmetric defence plan action, the network origin of the incident is overdrawn and the automatic plan of load shedding (by minimum frequency) will be put in action if the fixed thresholds are exceeded.

In complement of the wattmetric defence plan, a plan of load shedding by control to the active transit on the lines of interconnection is installed with an aim to decrease the transit on the interconnection lines below the thresholds of the wattmetric defence plan and ensure the help and the connexity of the networks. This plan of shedding is fixed according to the thresholds wattmetric strown on the

interconnection and the sizes of the groups installed (in order to ensure the safety N-1 groups).

4.4 Protection against the loss of synchronism (max θ)

Protections against the loss of synchronism installed at the level of the maghreb interconnections are of type DRS. The curve presents a recording of the voltage at the frontier station of the interconnection Morocco-Algeria following the release of two groups in Morocco at 26 january 1995 associated to releases of lines 225KV.

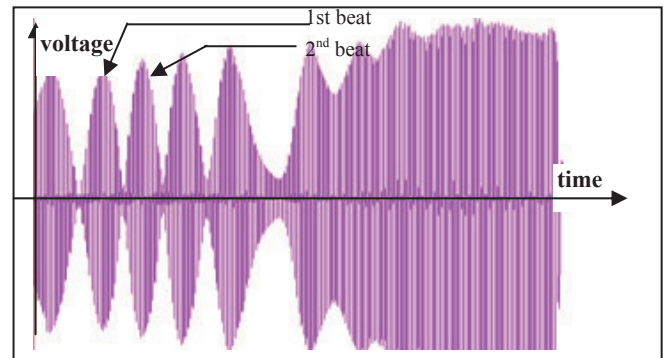


Figure 7: voltage oscillation against out of step

The following figure represents a recording of the 225kV voltage at the of interconnection station Tunisia-Algeria following a prolonged short circuit on a line serving the frontier network on April 09 / 2001.

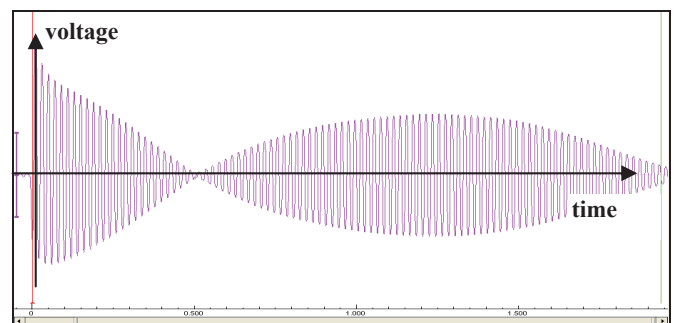


Figure 8: Volatge at the 225kV interconnection bus

Current adjustments:

Table 1 :

	SPAIN	MOROCCO	ALGERIA	TUNISIA
MOROCCO	65%Un, 2beat	-	70%Un, 1beat	-
ALGERIE	-	80%Un, 1beat	-	80%Un, 1beat
TUNISIA	-	-	80%Un, 1beat	-

4.5 Load shedding by minimum valtage

The load shedding by minimum voltage uses relays with minimum of tension and allows:

- ✓ to avoid the electrical supply to customers under abnormal conditions of voltage.
- ✓ to help the principal devices of the defence plan in failure.

Moroccan network:

- 15 stations are equipped by relays with minimum voltage to especially lighten local loads estimated at 20% of the peak power in the South network. These devices were set up in order :



- ✓ To especially avoid the collapse of the voltage at the level of the south network in the event of loss groups in western north
- ✓ To ensure the help of the system of load shedding controlled Wattmetric protection on the IME.

Algerian network:

- 8 stations high voltage and 12 stations middle voltage are equipped by relays with minimum voltage

Tunisian network:

- 2 stations are equipped with a relay which regulated minimum voltage with 85 %Un and which lightens 40% of the load in each station.

Libyan network:

- Under study in 10 stations especially on the Libyan south

4.6 Release of the Maghreb interconnections:

The table 2 gives the number of releases of the Maghreb interconnections by type of protection during the period 2002-2006.

Table 2:

	2002		2003		2004		2005		2006	
	RS	WP	RS	WP	RS	WP	RS	WP	RS	WP
Interconnection Morocco-Algeria	0	12	0	9	1	4	2	8	0	20
Interconnection Tunisia-Algeria	0	6	0	12	0	4	0	0	0	1

DRS : Synchronism Rupture Device

WP : Wattmetric Protection

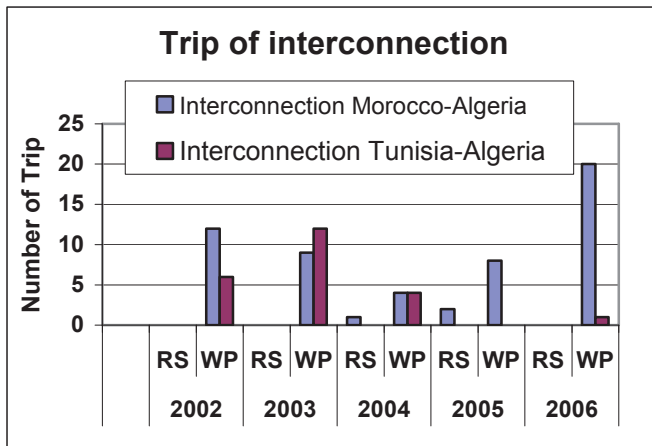


Figure 9 : Trip of tie lines interconnection in the electrical maghreb system

4.7 Coordination and exchange of information

The design of the defence plans and the determination of the adequate adjustments are significant but not sufficient. Periodic controls of operation for devices of safeguard of the network as well as the sensitizing of the personnel in charge of these controls, are essential for the reliability of the electric systems.

The defence plans of the grid systems require studies of operation and a control of the modeling of the inter-connected electric systems. The continuous effort for the development of experience sharing in the field of modeling

of the load and the systems of voltage regulation and speed prove to be necessary for the study group of the Commission of the Maghreb Interconnections.

5 Improvement activities and future recommendations

5.1. Optimization of the load shedding by mixed criteria

The power lightened in an electric system by a shedding by conventional minimum frequency (actual plan of shedding on the networks maghreb) is no optimal. It can lead to over/under shedding of load sometimes nonacceptable. The use of

a criterion $\frac{df}{dt}$ based on the rate of frequency variation is

recommended to optimize the load to be lightened according to the parameters variations of the system as well as the dynamics of the disturbance (quantity lost according to time).

The following figure shows the results of simulation in the event of production loss of 20% of the peak load for various loading cases 80%, 75% and 62% of the peak load in the Tunisian network, in the event of use of a traditional plan of shedding frequency – metric: Over shedding noted in simulations were the cases 62% and 75%.

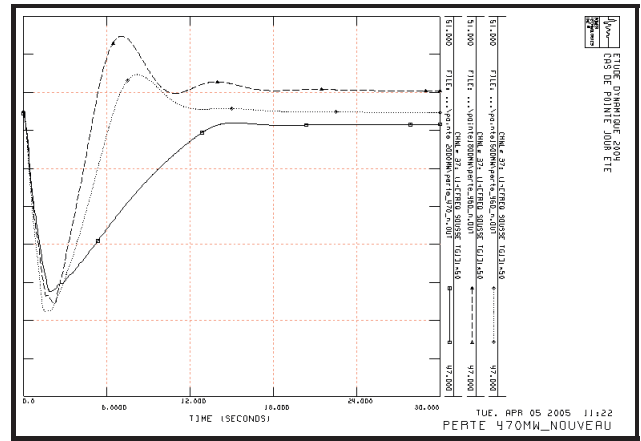


Figure 10 : Mixed criteria of the load shedding

The division of the shedding plan in two stages is necessary. These stages are:

- ✓ A first part which uses the conventional shedding functioning in the event of loss of low power and moderate power;
- ✓ Another which uses a mixed criterion of frequency and its derivative functioning in the event of loss of big size.

The table 3 recapitulates the automatic load shedding plan suggested (result of the study) and compared to the recommendations of the UNIPEDE (Union of Production Energy and Distribution of Electricity).

5.2. Defence Measures centralized in the Maghreb interconnections

The distribution of the adjustments on the various lines of the interconnections is a difficult spot since the distribution of the transits vary according to the production plan and the started production. The studies common at the maghreb scale (within the framework of the COMELEC) recommend a centralized measure of the sum of the transits on the various tie lines.



Table 3 :

Thresholds			Load shedding in %	Recommendations UNIPEDE
N°	F(Hz)	T(sec)		
1	49.30	0.2	5.4	1st threshold: 49 —48.8
	49.25	0.2	0.7	
	Total of the threshold		6.05	
2	49	0.2	5.9	2nd threshold: 48.7 —48.4
Total of the threshold			5.9	
3	48.7	0.2	-	
	48.7	10	-	
4	48.5	0.2	12.5	3rd threshold: 48.3 —48
Total of the threshold			12.5	
5	48.25	0.2	10.7	
Total of the threshold			10.7	15%
6	48	0.2	9.3	
Total of the threshold			9.3	
7	47.75	0.2	11.9	15%
	47.7	0.2	-	
Total of the threshold			11.9	
Total load shedding (in %)			56.25%	40 —50%

5.3. Future strategy of centralized defence

If local measures of defence can be qualified as corrective and functioning in closed loop, centralized or coordinated measures can be qualified as preventive and generally function in open loop. Indeed, they aim at keeping the integrity of the inter-connected system acting quickly in the initially disturbed networks to ensure its stability. They are qualified as centralized because they imply the centralization of information towards one or more decision-making centres and thus of telecommunications. They are also characterized by the pre calculation of measures of defence according to the disturbance met. They will be necessarily doubled by local defence measures which fill in this diagram the role of back up protection. The presence of centralized measures of defence requires the temporization of the local protections in order to allow time to the system to react to centralized measures and give to local measures a role of safeguard. The diagram of safety of the system thus becomes organized in 3 levels.

6. Conclusion

In conclusion, we think that it is not possible to be denied against any type risk. Indeed, we cannot conceive all the combinations of breakdowns or incidents likely to intervene on such a large number of components on the one hand, and it is not economically justified to defend oneself (if we want to preserve a normal operation of the system) against risks of which the probability of occurrence becomes extremely weak and independent. Thus, for combinations of particularly severe risks but far less probable, we accept degradations of the operation of the system leading to significant effects on the customers. The priority is then to preserve the control of the evolution of the incidents in order to limit their final impact. In more serious cases, one possibly agrees to sacrifice a reduced part of the system.

The design of the Maghreb defence plans is based on the same techniques of safeguard, nevertheless the application of these techniques depends on the structure of the electric system: topology of the network, site of production... etc.

The adjustments of protections adopted on the lines of the Maghreb interconnections, although they did not make it possible to ensure the mutual help and solidarity in term of frequency, showed a certain effectiveness to avoid the propagation of the incidents to the close countries

With the development of the maghreb electric systems by the installation of the power stages of the significant groups, the reinforcement of the internal networks and the possibilities of extension of the synchronism zone, the defence plans must be revised and coordinated permanently and this in order to support trade and the mutual helps while preserving the safety of the electric systems.

Table 4 :

Level	1	2	3
Nature	Preventive liability	Preventive credit	Corrective measure credit
Objective	Maintenance of the system inter-connected	Maintenance of the system inter-connected	The stability of the system inter-connected is lost. Opening of the sections critical to stop the losses of synchronism.
Activation	Disturbance less severe than the normative disturbance (called dimensioning incident).	Disturbance more severe than normative disturbance. Activation can be anticipated for disturbances less severe than the disturbance normative.	Disturbance more severe than normative disturbance and absence or faulty operation of measurements of centralized defences. No respect of the margins of safety on the critical sections,
Means	Definition of the incidents dimensioning the Margin on the capacities of transfer	Tele shedding of load to remain below side levels of exchanges max on the sections. Fast decrease (transitory or permanent) of the produced mechanical power	Opening of the sections on local criteria shedding of load Parcelling out of the network in zones Preset isolation of group of production from their auxiliaries



7. References

- [1] Jacques Neirynck "Treated of electricity of the federal polytechnic school of Lausanne ", Volume XII, electric Power (edition 1992).
- [2] C Barret J.P "Year analysis of phenomena of voltage collapse one has transmission system Barbier ". general review of electricity, special number; p3-21, 1980.
- [3] Said Abdellaziz, Chokri Bouchoucha, Khdiya Kilani, "Voltage stability evaluation of the interconnected modal Tunisian power system by the analysis technical ", Third IEEE International Conference one system, signals and Devices; march 2005, Tunisia.
- [4] Said Abdellaziz, Khdiya Kilani " Voltage stability modal analysis of power systems modeling and application", Third IEEE International Conference on system signals and Devices; march 2005, Tunisia.
- [5] R. Kundour " Power system Stability and control", Edition 1996.
- [6] F.Gubina, D.Grgic; New B.Strmcnik "approaches the évaluat ion of the instability of tension ", CIGRE 1998 Session - august-paper 39-110.
- [7] W.I. Rowen «Simplified Mathematical Representation s of Heavy-Duty Gas Turbines», Oktober 1983, Journal of Engineering for Power.
- [8] Simplified Mathematical Representations of Single Shaft Gas Turbines in Mechanical Drive Service » W.I. Rowen, June 1992, ASME.
- [9] Pratique de différents exploitants réseaux dans le monde : «Analysis and control of power system scillation» , Task force 07, study committee 38, December 1996.
- [10] Feasibility study of the interconnection of the electrical supply networks in 500 / 400 Kv of Egypt - Libya-Tunisia-Algeria - Morocco, B2 Spot: Dynamic study, 2003-2004.
- [11] J Chatelain "electric Machine, polytechnic school of Lausanne, Switzerland, Volume X, CH 105 Lausanne, edition 1994.
- [12] JF Hauer, CJ Demeure and LL Scharf IEEE transactions on power systems,. February 1990, Vol 5 No 1 pp 80-89.
- [13] "Industry Experience with Special Portection Schemes" , IEEE/CIGRE Committee Report, IEEE Transactions on Power Systems, vol 11, N° 3, Augsut 1996.
- [14] G. Trudel, S Bernard, G Scott «Hydro-Quebec defence pla n against extreme contingencies» , IEEE transactions on Power Systems, vol 14, n° 3, August 1999.
- [15] N.V. Kosterev, V.P. Yanovsky, D.N. Kosterev « Modelling of Out-of-Step Conditions in Power Systems » , IEEE Transactions on Power Systems , vol 11, N° 2, May 1996.
- [16] A. Bondarenko, V. Gerikh « Emergency Control in UES of Russia , , IEEE Transactions on Power Systems, vol 11, N° 2, May 1996.
- [17] R. DUGUAN, D. SABIN, E.LEINFUSS, Electrotek Concepts.Signatures of the black out of 2003. 6 octobre 2003.
- [18] Résumé du groupe 39 « Lessons learnt and to be learn from the 2003 black out» , , Cigré WG C2.03. 2004.
- [19] ICF Consulting " The economic cost of the black out", an issue paper on the northeastern black out, aout 14 2003.
- [20] Rapport finale UCTE « Interim report of the investigation commuttee on the 28 september 2003 black out in Italy» , , 26 October 2003.
- [21] P. KUNDUR K. MORISON « Practical Consideration in Voltage Stability Assesement» , , Electrical Power and Energy Systems, No. 4, 1993.
- [22] G. MATUSZ, T. MAJ, Z. HANZELKA « Voltage disps and short interruptions- différents strategies in contrac t for the electric power supply » , , CIGRE 04, papier C4-107 ; Aout 2004.
- [23] Report/ratio of a working group IEEE/CIGRE, "the industrial experiment of the special protection systems " IEEE CIGRE1986.
- [24] C.BOUCHOCHA and S. CHEBBI and S.MEJRI and Mr. ANNABI, Validation Study of Maghrab Europe Electric Power Interconnect, International ICGST Newspaper one Automatic Control and System Engineering ACSE, P1110704002, volume 7, July 2007.





Robust Control for a Class of Nonlinear Systems

Tlili saber¹, Mibar hassan²

Unit of research (RME), INSAT, Tunisia

Centre urbain Nord, B.P. N°676, 1080 Tunis Cedex, Tunisia

¹ tlili_saber2003@yahoo.fr, ²hassen.mibar@enit.rnu.tn

Abstract

This paper is concerned with the control problem synthesis for nonlinear systems using linear technique. The proposed algorithm consists on an approximation of the non-linear systems by a set of uncertain linear models and presents a systematic approach for non-linear control design by using the gain scheduling technique to insure the transition of a non-linear dynamical process from an actual operating condition to a desired one. The non-linear system is represented in neighbourhood of equilibrium points by a family of uncertain linear systems. A robust control law is built so as to insure asymptotic stability to a given equilibrium within a maximal ellipsoidal region. Given a pre-specified equilibrium curve connecting the initial and final points. Output feedback for the local robust control synthesis are considered, together with local performance criteria. A simple numerical experiment is provided to illustrate both the effectiveness of the synthesis and the performance achieved.

Keywords: Robust control, Gain Scheduling, Transition Control, Norm bounded uncertainties, Linear Matrix Inequalities (LMI).

1. Introduction

The majority of control laws implemented in industry are still designed and analysed using predominantly linear techniques applied to linearized models. Given the continuous increase in the demands on their performance and reliability, control law designers are highly motivated to explore the applicability of more powerful design and analysis tools allowing to take into account both nonlinearities and parametric variations. In this context, new robustness analysis and robust control synthesis methods are first developed for systems presenting an adaptive controller or a varying controller structure. The common approach to solve a complex problem is to use the strategy of divide and conquer. This strategy leads to multiple models or multiple controllers approaches to deal with nonlinear

systems. Some of the approaches used frequently are: multiple models adaptive control, supervisory control, the quasi-LPV approach [19] and gain scheduling [18].

Gain scheduling dynamic controllers for a nonlinear plants are studied in [3]. One can find in [14] approaches to design controllers for linear parameter-varying systems. Takagi-Sugeno fuzzy gain-schedulers are proposed in [1] and in [12]. A generalized gain scheduling approach is developed in [6].

Gain scheduled control technique is based on the existence of several, generally linear, models which are assumed to be valid for the representation of a system to be controlled in different subsets of the state space. Obviously, for a complete characterization, the union of the subsets covers the state space domain of interest. For a nonlinear system, the models can be obtained by linearization at several different feasible equilibrium points, referred to by trim points in the sequel. Different controllers are designed for each linear model.

In this work, we develop an alternative gain scheduling procedure that exhibits some of the performance properties of standard gain scheduling, but provides stability guarantees between the scheduling points. In particular, we consider the use of the gain scheduling approach to the problem of stable guaranteed transition from an actual operating point to a desired one by using a pre-specified path in the equilibrium manifold of the non-linear system connecting the operating points. An uncertain linear system is used to describe the non-linear system in a ellipsoidal region around an equilibrium point. A Lyapunov function for the uncertain linear system is used to estimate ellipsoidal stability regions of the non-linear system. Repeating the procedure on the pre-specified path in the equilibrium manifold connecting the two operating conditions, we can cover the path by a set of ellipsoids. The algorithm developed assure closed loop stability of the non-linear system and local performance .



The paper is organized as follows: Section 2 gives a description of the HL-CPWL approach. Section 3 concerns the local robust control laws synthesis : robust H_2 filter. We end the paper by an illustrative example and a conclusion.

2. A High level Canonical Piecewise modelling: HL-CPWL approach

Consider the class of discrete nonlinear systems described by the following state space equations and the following remarks:

$$\begin{cases} \dot{x} = g(x(t), u(t)) + B_1 w(t) + B_2 u(t) \\ y = C x(t) \\ x = [x_1 \ x_2 \dots x_n] \in R^n \quad u = [u_1 \ u_2 \dots u_m] \in R^m \\ y \in R^q \quad w \in R^p \end{cases} \quad (1)$$

with

$$\begin{cases} g(x(t), u(t)) = A_n x(t) + B_n h(x(t), u(t)) \end{cases} \quad (2)$$

where

$$h(x(t), u(t)) \rightarrow h(\xi(t)) = [h_1(\xi(t)) \ h_2(\xi(t)) \dots \ h_n(\xi(t))]^T \quad (3)$$

$g(x)$ is a nonlinear function.

$x \in R^n$, $u \in \mathfrak{R}^m$, $y \in \mathfrak{R}^p$ and $w \in \mathfrak{R}^q$ are respectively the state, the control, the measured outputs and the perturbation.

We are interested in continuous time SISO or MIMO state space representation of systems.

Systems are state nonlinear and/or control nonlinear. It can exist one or more non-linearities depending on one or two state variables and/or control variables.

The linear part accepts a non null dynamical matrix A_n .

The main steps of the procedure are described below and the next subsections are devoted to large explanations of each step of the HL-CPWL approach. The algorithm is composed of four steps

2.1 Approximation of nonlinearities function

In this section we introduce the basic aspects which are common to all types of PWL representations. We begin by briefly recall PWL functions, intersection and Simplex[7].

Definition 1 : PWL functions

Let the domain is partitioned into a set of convex polyhedrons called regions $E^{(i)}$ so that

$$S = \bigcup_{i=1}^N E^{(i)} = E^{(1)} \cup E^{(2)} \dots \cup E^{(N)} \quad (4)$$

by a set $R = \{ R_i \subset S, i = 1 \dots N \}$ of a finite number of n -dimensional hyperplanes, also called boundaries:

$$R_i = \{ x \in R^n : \pi_i(x) = \alpha_i^T x - \beta_i = 0 \} \quad (5)$$

where $\alpha_i \in R^n$, $\beta_i \in R \ \forall i = 1 \dots N$. Then, a PWL function is defined by the local (linear) functions :

$$f^{(i)}(x) = J^{(i)}x + \varpi^{(i)} \quad (6)$$

with $x \in E^{(i)}$, $J^{(i)} \in R^{m \times n}$ and $\varpi^{(i)} \in R^m$. Moreover if $J^{(i)}x + \varpi^{(i)} = J^{(k)}x + \varpi^{(k)}$, $\forall x \in E^{(i)} \cap E^{(k)}$

Definition 2: Intersection

In a partition of the domain $D \subset R^n$, an $n-1$ dimensional hyper-plane is said to be a first-order intersection, denoted by $S^{(1)}$. A linear manifold of dimension $(n-k)$ in D is a k th-order intersection $S^{(k)}$ if it is the intersection of two or more linear manifolds of type $S^{(k-1)}$, ie.,

$$S^{(k)} := \bigcap_{i=1}^{\geq 2} S_i^{(k-1)} \quad (7)$$

Definition 3 : Simplex

Let $x_0, x_1, \dots, x_n$ be $n+1$ vectors in R^n . A simplex $S^{(i)} \triangleq \Delta(x_0, x_1, \dots, x_n)$ is defined as

$$\Delta(x_0, x_1, \dots, x_n) = \left\{ x \in R^n : x = \sum_{i=0}^n \mu_i x_i \right\} \quad (8)$$

where $0 \leq \mu_i \leq 1$ and $\sum_{i=0}^n \mu_i = 1$, for $i = 0, 1, \dots, n$

The interest of these HL-CPWL functions comes from their systematic writing for any functions. Then, it will well suit for functions, which represent non-linearities in systems.

We consider rectangular compact domains in R^n of the form

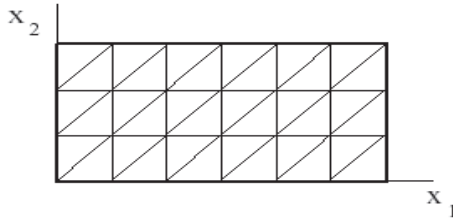
$$S = \{ x \in R^n : 0 \leq x_i \leq m_i \sigma_i, i = 1, 2, \dots, n \} \quad (9)$$

Where σ_i and m_i are a grid step and the number of cells associated with x^i axis.

Each dimensional component x^i of a compact domain S can be subdivided into m_i subintervals of amplitude $\sigma_i = (\underline{x} + \bar{x}) / m_i$. As a result, S turns out to be partitioned into $\prod_{i=1}^n m_i$ hyper rectangles and to contain $N = \prod_{i=1}^n m_i + 1$ vertices.

For as example, we introduce a non-linear function defined in R^2 . The simplicial partition of the hyper rectangle $[0, \sigma_1] \times [0, \sigma_2]$ in the simplices $\Delta(0, (\sigma_1, 0), (\sigma_1, \sigma_2))$, $\Delta(0, (0, \sigma_2), (\sigma_1, \sigma_2))$.



Figure.1 A Simplicial partition of a domain in R^2

It is important to note that the HL-CPWL function possesses the minimum number of parameters required to represent the PWL function $\mathcal{G}$. This follows from the fact that all the information that is necessary to characterize the function $\mathcal{G}$ is given by the function values on the vertices.

With a fixed number σ_i of hyperplanes, one can design the approximation $\mathcal{G}_{HLCPWL}$ of g , for an arbitrary precision that

$$\mathcal{G}_{HL-CPWL}(x) = C^T \Lambda(x) \quad (10)$$

The matrices $\Lambda(x)$ and C^T are constructed according to the HL-CPWL.[7,15]

Now, we can apply to the considered class of nonlinear systems (1)-(3) which is rewritten by

$$\begin{cases} \dot{x} = \mathcal{G}_{HL-CPWL}(x) + B_1 w(t) + B_2 u(t) \\ y = C x(t) \end{cases} \quad (11)$$

$$\text{with } \mathcal{G}_{HL-CPWL}(x) = \begin{pmatrix} h_{1HLCPWL}(x) \\ h_{kHLCPWL}(x) \\ \vdots \\ h_{nHLCPWL}(x) \end{pmatrix} \quad (12)$$

$$\text{and } h_{i,HLCPWL}(x) = A_i x(t) + b_i \quad (13)$$

2.2 Design of uncertain LTI systems

Let's consider the piecewise linear model (11)-(13). In this section is given the way we have chosen the breaks and the intermediate equilibriums points from the piecewise-linear approximation of non-linearity's.

Determination breaks points

In the subsection is given the way we have chosen the break $(BP_j, BP_{j+1}, \dots)$ points from the HLCPWL approximation of the non-linearity. Figure 2 depicts a nonlinear function $g(x)$, $\mathcal{G}_{HL-CPWL}(x)$ and the break points BP_i .

These points are considered for each model uncertainty : limits validities domain.

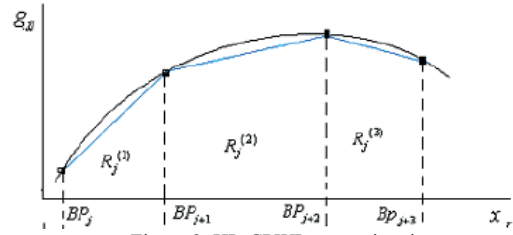


Figure.2 HL-CPWL approximation

Determination intermediate equilibriums points

The intermediate equilibriums points will be determined as the middle of the validity domain of each hyperplans bounded by two consecutive breaks points BP_j, BP_{j+1} .

$$x_{eq,j} = \frac{BP_j + BP_{j+1}}{2} \quad \forall j = 1, \dots, N \quad (14)$$

Determination the uncertainty domain

The norm bounded uncertainty are defined as follows

$$\Delta A = D_i F_i E_i \quad (15)$$

$D_i \in \mathbb{R}^{n \times r}$ and $E_i \in \mathbb{R}^{l \times n}$ are the matrix constants. The uncertain matrix belongs to the following:

$$F_i = \{F_i \in \mathbb{R}^{r \times l} : F_i^T F_i \leq I\} \quad (16)$$

The calculus of each ellipsoid domain of uncertainty of each non linearity is

if $g_i(x)$ is one argument function $x_i = [x_{1,i}]$ then

$$D_i = I \text{ and } E_i = \alpha_i \text{ with } \alpha_i = x_{eq,i+1} - x_{eq,i}$$

if $g_i(x)$ is two argument function $x = [x_{1,i} \ x_{2,i}]$ then

$$D_i = I, \text{ and } E_i = [\alpha_i \ \beta_i] \text{ with } \alpha_i \text{ and } \beta_i \text{ are represented respectively the two axis of ellipse } \xi_i$$

$$\alpha_i = x_{eq,1,i+1} - x_{eq,1,i} \text{ and}$$

$$\beta_i = x_{eq,2,k+1} - x_{eq,2,k}$$

The last condition for the adjacent equilibriums points is mandatory for being able to apply the switching between two state space subsets. This condition is also important for the stabilization, which is described, in the following step.

By this way, we can consider, for each state-space subset, one equilibrium point and associate one uncertain local linear model

$$\begin{cases} \dot{x}(t) = (A_i + \Delta A)x(t) + B_2 u(t) + B_1 w(t) + b_i \quad \forall i = 1 \dots N \\ y(t) = C x(t) \end{cases} \quad (17)$$

$$\forall x(t) \in X_i$$

With X_i is the variation domain of the state variables.



The equation (17) represents a problem at the level of the term β_i . For this reason we must eliminate this term, in order to relocate the state vector $x(t)$ by a constant x_0 .

Let's suppose now that, we have a new state variable $z(t)$ where $z(t) = x(t) - x_0$, $\dot{z}(t) = \dot{x}(t)$.

Now, we can apply to the considered class of linear model (17), which is rewritten by

$$\begin{cases} \dot{z}(t) = (A_i + \Delta A_i)z(t) + B_2 u(t) + B_1 w(t) \\ y(t) = C z(t) \end{cases} \quad \forall i = 1, \dots, N \quad (18)$$

$$\forall z(t) \in Z_i$$

with Z_i the variation domain of the state variables $X_i - X_{0i}$.

2.3 Local robust synthesis

The next section is devoted to large explanations of robust synthesis for a family of continuous time bounded norm uncertainly linear systems.

2.4 Global control law by scheduling

The last step for this algorithm is to calculate, for each uncertain linear model, a constant local control law which is different from one equilibrium point to another one. This family of constant local control laws permits to reach every equilibrium points from each adjacent equilibrium points taken as initial condition. It may take a long time to reach them, but we assume that when the current state is sufficient near the intermediate equilibrium point, the switching between two state space subsets may happen. By this way, the proposed approach ensures a robust control synthesis. The smooth switching is obtained with the sufficient conditions of inclusion.

3. Robust H_2 Filter

Let the uncertain continuous-time invariant linear system be described by

$$\begin{cases} \dot{x} = (A_i + D_i F E_i)x + B_1 w \\ y = Cx \\ z = Hx \end{cases} \quad F'F \leq I \quad (19)$$

where where, $x \in R^n$, $u \in R^m$, $y \in R^p$ and $z \in R^r$ are the state, the control, the measured output, and the output estimates vectors. Furthermore, w represents an exogenous signal and $H_{zw}(s)$ denotes the transfer matrix function from w to z .

The basic problem to be formulated is the stabilizability problem with respect to the strictly proper filter

$$\begin{cases} \dot{x}_o = A_o x_o + B_o y \\ z_o = C_o x_o \end{cases} \quad (20)$$

We can determine the matrices A_o, B_o and C_o if $z_o \rightarrow z$. For this reason we have identified a problem of type H_2 on the system extended

$$\begin{cases} \dot{x} = (A + DFE)x + B_1 w \\ \dot{x}_o = A_o x_o + B_o y \\ \varepsilon = Hx - C_o x_o \end{cases} \quad (21)$$

with ε the error signal and w perturbation.

In this section, a performance specification is added to the previous stabilizability problem, the problem being to find a filter of class (20) that keeps the H_2 norm of the transfer function $H_{zw}(s)$ as small as possible.

Provided matrix A_g in (23) is Hurwitz, the square of this norm can be expressed in terms of the solution to a Lyapunov equation (observability Grammian) such that this minimization problem with respect to the triplet of variable (A_o, B_o, C_o) is given by

$$\min(A_o, B_o, C_o) \mu$$

$$\forall F: F'F \leq I, \|C_g(pI - A_g - D_g F E_g)^{-1} B_g\|_2^2 < \mu \quad (22)$$

where

$$A_g = \begin{bmatrix} A & 0 \\ B_o C & A_o \end{bmatrix}, B_g = \begin{bmatrix} B_1 \\ 0 \end{bmatrix}, C_g = [H \quad -C_o], \quad (23)$$

$$D_g = \begin{bmatrix} D \\ 0 \end{bmatrix} \text{ and } E_g = [E \quad 0]$$

The command with observers increased returns to the terms of this uncertainty as:

$$\begin{cases} \min \text{trace } W \\ W > B_g' P B_g \\ A_g' P + P A_g + C_g' C_g + P D_g D_g' P + E_g' E_g < 0 \end{cases} \quad (25)$$

which, using Schur complement and transformation can be rewritten in the equivalent form

$$\min \text{trace } W$$

$$\begin{bmatrix} W & B_1' & B_1' X \\ B_1 & Y & I \\ X B_1 & I & X \end{bmatrix} > 0 \quad (26)$$

$$\begin{bmatrix} AY + YA' & Z + M & YH' - L' & D & YE' \\ Z' + M' & A'X + XA + FC + C'F' & H' & XD & E' \\ HY - L & H & -I & 0 & 0 \\ D' & D'X & 0 & -I & 0 \\ EY & E & 0 & 0 & -I \end{bmatrix} < 0$$

with

$$L = C_o V', \quad F = U B_o, \quad M = V A_o' U' \text{ and}$$

$$Z = A + Y A' X + Y C' F'$$

A numerical example to valid our method is provided in the next section.



4. Numerical Example

Consider the Tree Tanks system shown in Fig.3, and described by the set of state space equation (27) .

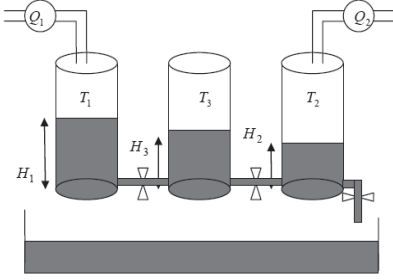


Figure 3: Tree Tank system

$$\begin{cases} \dot{x}_1 = -K_{13}\sqrt{|x_1 - x_3|} + \frac{1}{S}u_1 \\ \dot{x}_2 = -K_{32}\sqrt{|x_3 - x_2|} - K_{20}\sqrt{x_2} + \frac{1}{S}u_2 \\ \dot{x}_3 = K_{13}\sqrt{|x_1 - x_3|} - K_{32}\sqrt{|x_3 - x_2|} \end{cases} \quad (27)$$

with

$$K_{13} = \frac{\lambda_{13} \times S_c \times \text{sgn}(H_1(t) - H_3(t)) \times \sqrt{2 \times g}}{S},$$

$$K_{32} = \frac{\lambda_{32} \times S_c \times \text{sgn}(H_3(t) - H_2(t)) \times \sqrt{2 \times g}}{S} \text{ and}$$

$$K_{20} = \frac{\lambda_{20} \times S_c \times \sqrt{2 \times g}}{S}.$$

$$x = \begin{bmatrix} H_1 \\ H_2 \\ H_3 \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}, \quad u = \begin{bmatrix} Q_1 \\ Q_2 \end{bmatrix} = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$$

where, $x \in \mathbb{R}^n$ and $u \in \mathbb{R}^m$ are respectively the state vector and the input vector.

The system present two nonlinear functions two arguments and one nonlinear function one arguments , we consider the index r a number of nonlinear function in the system. ($r = 3$ in this system) .

where $D_k = I$

$$\text{and } E_k = \begin{pmatrix} \alpha_k & 0 & \beta_k \\ 0 & (\alpha_k + \beta_k) & \alpha_k \\ \alpha_k & \beta_k & (\alpha_k + \beta_k) \end{pmatrix}$$

with

k	η	ω	α	β
1	-0.774	0.6754	0.25	0.62
2	0.5477	0.368	0.23	0.53
3	-0.5476	0.368	0.29	0.59
4	0.773	0.6755	0.32	0.67

For this example, we chose to limit the variation domain in levels of tanks at the interval $[0, 60]$ and the number of local models uncertain is 2 models ($N = 2$). The application of the HL-CPWL representation on the nonlinear functions

$$h_i^r = \sqrt{x_{2,i}}, r=1, i=1 \dots 2,$$

$$h_i^r = \sqrt{|x_{1,i} - x_{3,i}|}, r=2, i=1 \dots 2 \text{ and}$$

$$h_i^r = \sqrt{|x_{3,i} - x_{2,i}|}, r=3, i=1 \dots 2$$

Can determine the intermediate equilibrium points (table 1).

Table I.1 : Equilibrium points value

i	1	2
$x_{eq,i}$	12,52	37,52

Fig.4(a -b) depicts the both non linearities h_i^r and its approximation.

In this example we have 4 models in the following domain which corresponds to a good enough approximation of the non linearity.

The analytic function of the nonlinear functions approximation is

$$f_{HL-CPWL}(x) = \sum_{k=1}^4 (\eta_k x_i + b_k) + (\omega_k x_j + \delta_k) \quad i = \{1, 2\} \text{ and } j = \{1, 2\}.$$

The determination of different equilibrium points and the number of linear models can define the parameters of the uncertainly domain elliptical for each linear model.

The uncertain linear multi-model constructed is given by

$$\dot{Z} = \left[\begin{array}{ccc} -K_{13}\eta_k & 0 & -K_{13}\omega_k \\ 0 & -(K_{32}\omega_k + K_{20}\eta_k) & -K_{32}\eta_k \\ K_{13}\eta_k & K_{32}\omega_k & K_{13}\omega_k - K_{32}\eta_k \end{array} \right] + D_k F_k E_k \quad Z$$

$$+ \left[\begin{array}{cc} \frac{1}{S} & 0 \\ 0 & \frac{1}{S} \end{array} \right] \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$$

Robust H_2 Filter

It is interesting now to apply the proposed method to design the robust H_2 filter (26) for (27) formulated from (19) with a disturbance w and for the same nonlinearities.

The control objectif is to drive the state variables $[H_1 \ H_2 \ H_3]$ from an initial values $[0 \ 40 \ 30]^T$ to the target equilibrium points $[29 \ 19 \ 30]^T$.

Fig. 6a shows the switching between state subspaces and the both responses have reasonably good transient performances thanks to the uncertain domain choice and the Fig. 6b shows the gain scheduling control.



This technique ensures stable transition between the starting point and destination by four corrector. For the latter, there are discontinuities in commutation moments, the amplitude of these discontinuities decreases with the increase in the number of corrector. The algorithm permits to tune the complexity of the global control law and the gain scheduling technique with the cardinality of the set of local linear systems.

5. Conclusion

In this paper, we have proposed an algorithm that approximate non-linear systems by a high level canonical piecewise linear and the algorithm guarantees the closed loop stable transition of a nonlinear system from an actual operating point to a desired one. A norm bounded uncertain linear system is used to describe the nonlinear system in a ellipsoid region around an equilibrium point. The robust control laws scheduling is executed when the state trajectory reaches the attraction domain of the following equilibrium point. The scheduling policy is based on the belonging of the estimated state to the stability ellipsoid of the next equilibrium point.

Although we have restricted ourselves here to a simple class of nonlinear systems, nonlinear systems with one non-linearity and two non-linearity, such an approach can be extended to larger class of nonlinear systems.

6. References

- [1] D. Driankov, R. Palm, and U. Rehffuss, "A takagi-sugeno fuzzy gainscheduler," in Proc. IEEE Conf. Fuzzy Syst., New Orleans, LA, 1996, pp. 1053-1059.
- [2] D. Henrion, "Stabilité des Systèmes Linéaires Incertains à Commande Contrainte", PhD thesis, Institut National des Sciences Appliquées, 1999.
- [3] D. Leith and W. Leithead, "Gain Scheduling and Nonlinear Systems Dynamic Analysis by Velocity Based Linearisation Families", Int. J. Control, vol. 70, 1998, pages 289-317.
- [4] D. Leith and W. Leithead, "Gain Scheduling Controller Design : an Analytic framework directly incorporating non equilibrium Plant Dynamics", Int. J. Control, vol. 70, 1998, pages 249-269.
- [5] J. Shamma and M. Athans, "Analysis of non Linear Gain Scheduled Control Systems", IEEE Transactions on Automat Control, vol. 35, 1990, pages 898-907.
- [6] K. Hunt and T. Johansen, "Design and analysis of gain-scheduled control using local controller networks," in Int. J. Contr., vol. 66(5), 1997, pp. 619-651.
- [7] P. Julián, A. Desages and O. Agamennoni, "High-Level Canonical Piecewise Linear Representation Using a simplicial Partition," IEEE Trans. on circuits and Systems, Vol. 46, N° 4, pp. 461-480. 1999
- [8] P. Julian, M. Jordan, and A. Desages, "Canonical piecewise-linear approximation of smooth functions," in IEEE Trans. on Circuits and Systems, 1998.
- [9] P. Teppa, "Approche par Séquencement de Gains Robuste pour la Commande de Système Non Linéaire", 3 ème Congrès des Doctorats, Toulouse, France, , 2002.
- [10] L. O.Chua and A. Deng "Canonical piecewiselinear representation," IEEE Trans. circuits Syst. I, Vol. CAS-35, pp. 511-525. 1988
- [11] L.O. Chua and S. Kang, "Section-wise piecewise-linear functions: Canonical representation, properties, and applications," Proc. IEEE, Vol. 65, pp. 915-929, 1977
- [12] R. Palm, D. Driankov, and U. Rehffuss, "Lyapunov linearization based design of takagi-sugeno fuzzy controllers," in Proc. IFSA World Congress., Sao Paulo, Brazil, 1995, pp. 513-516.
- [13] S. Kang and L. Chua, "A global representation of multi dimensional piecewise-linear functions with linear partitions," IEEE Trans. on circuits and Systems, Vol. CAS-25, pp. 938-940. 1978
- [14] S. Sharuz and S. Behtash, "Design controllers for linear parameter-varying systems by the gain scheduling technique," in J. Math. Anal. Applicat., vol. 168, 1992, pp. 195-217.
- [15] S. Tlili, H. Mibar, A Method for Approximation and Control of Non-linear Systems, International Journal on Sciences and Techniques of Automatic control, ISSN 1737-7749.
- [16] V. Chellaboina, A. Leonessa and M. Haddah, "Nonlinear system stabilization via equilibria-dependent lyapunov functions : Beyond gain scheduling control", Systems and Control Letters, vol. 19, 1998, pages 23-27.
- [17] W. Bequette and K. Schott, "Control of Chemical Reactors Using Multiples Models Adaptive Control", proceedings of IFAC. Dinamarca, vol. 8, Denmark, july 1995, pages 149-152.
- [18] W. Rugh, "Analytical Framework for Gain Scheduling", IEEE Control Systems magazine, vol. 11, 1991, pages 97-84.
- [19] W. Rugh and J. Shamma, "Research on Gain Scheduling", Automatica, vol. 36, 2000, pages 1401-1425.



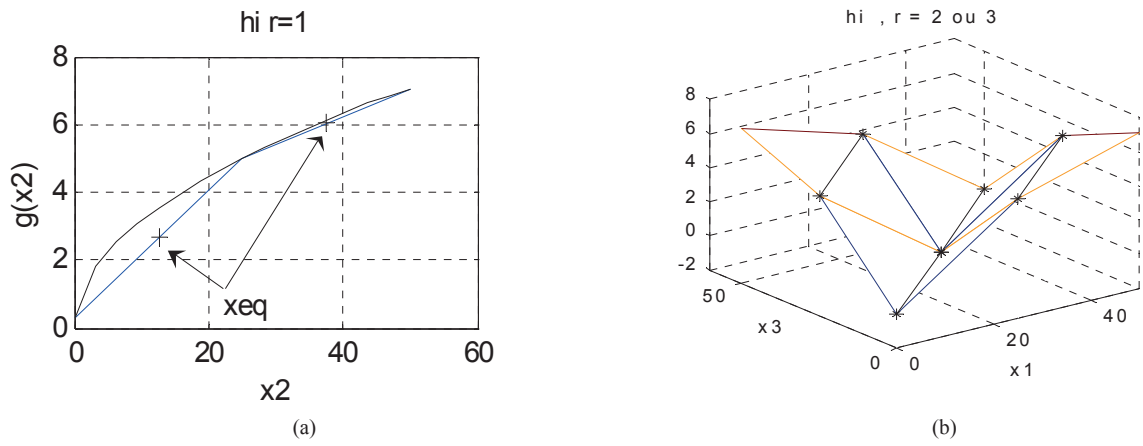


Figure 4 : Non linearities h_i^r function and approximation

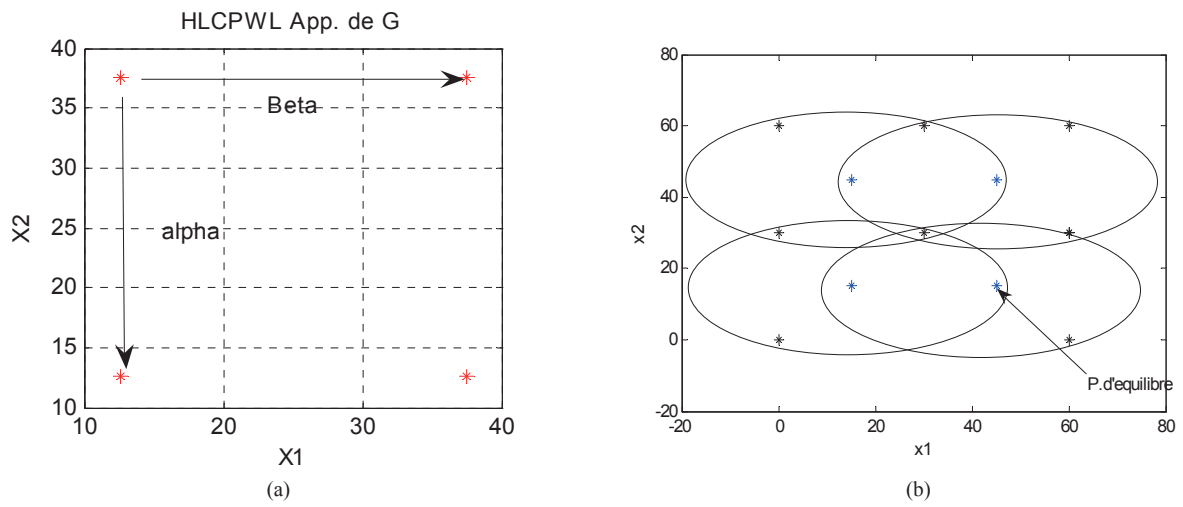


Figure 5 : (a) α and β parameters (b) uncertainly doamin elliptical

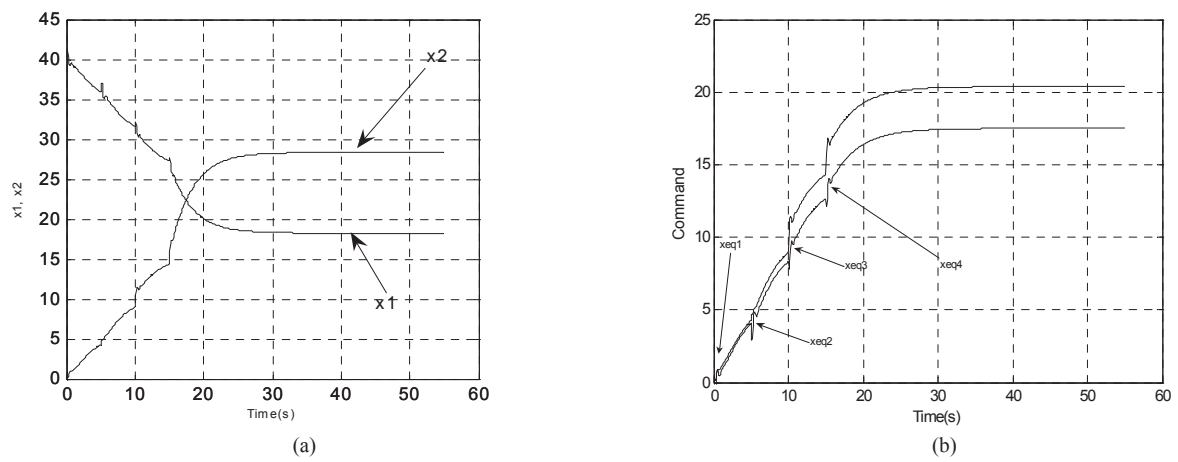


Figure 6: (a) State variable (b) Gain scheduling control



7. Biography



Saber Tlili is born in Tunis (Tunisia) in 1979. he received the master of Industrial Informatic and automatics from National Institute of Applied Sciences and Technology (INSAT) in 2005. Currently, he is permanent assistant in Higher Institute of Computer Sciences of Medenine and research member of *Unit of research (RME) in INSAT* . He is preparing the thesis on electrical engineering.



A/Prof. Dr. Hassen Mibar was born in Zarzis (Tunisia) in 1971. He received the M.Sc. degree in Electrical Engineering and the D.Sc. Degree in Control Engineering from ENSET, Tunisia, respectively. In 2001. He is graduated from National Engineering school of Tunis, ENIT and received the Ph.D. degree in Electrical Engineering. Since 2001, Dr. Hassen Mibar is a permanent Associate Professor at Higher Institute of Applied Sciences and Technology of Sousse. His fields of interest include distributed parameter systems, non linear systems, robust observers and robust control..





Greenhouse Model Identification based on Fuzzy Clustering Approach

A. Errahmani*, M. Benyakhlef** and I. Boumhidi*

* LESSI, Département de physique, Faculté des Sciences Dhar El Mehraz.

BP 1796 Atlas Fez 30 000 MOROCCO

** Faculté Poly disciplinaire Taza

aerrahmani@menara.ma, mbenyakhlef@netcourrier.com

Abstract

Fuzzy modelling has been widely applied as a powerful methodology for the identification of nonlinear system from process measurements. This work proposes a contribution on the application of fuzzy logic to identification of a class of large scale system with multiple models. The researched models have black box structure and the rules are determined by numerical approaches. The proposed approach is developed by using fuzzy clustering and is applied on a real system which is nonlinear in nature (greenhouse).

Keywords: Identification of nonlinear systems, Fuzzy clustering, greenhouse climate modelling.

1. Introduction

Recently, there is a huge demand for tools that can be used for identification of complex nonlinear process which are difficult to describe mathematically. In the literature technique for mathematical modelling for real process are classified in two categories: physical modelling and system identification [6]. The first is based in terms of the physical laws involved in the process and the second is based on the analysis of the process input output data and from empirical expertise by using fuzzy logic which effective for approximation of uncertain non linear dynamics systems. Generally, modelling process consists to obtain a parametric model with the same dynamic behaviour of the real process. However, when the process is complex, it is very difficult to define the different mathematical or physical laws which describe here behaviour [2], [1]. Numerous approaches have been proposed [4] which compute nonlinear dynamic fuzzy models from input/output measurement data [7] or neuro-fuzzy approaches [5].

The fundamental goal of this work is addressed of fuzzy modelling by using an algorithm that implement fuzzy clustering.

The proposed algorithm is based on decomposition of the fuzzy relation into sub relations, through a process of unfolding the fuzzy rules. The obtained sub rules are then grouped into subgroups (clusters). The number of the

clusters is defined on line. The clusters obtained with this fuzzy clustering algorithm are used to compose the new fuzzy submodels. The proposed approach is applied to model the greenhouse air temperature and humidity under process control. Each fuzzy submodel defined reflects the behaviour of one real physical sub model.

The paper is organized as follows: section 2 explains the identification of fuzzy model, in section 3, we describe the greenhouse climate model, in section 4 we introduce a fuzzy clustering algorithm, simulation results are given to demonstrate the effectiveness of the proposed approach in section 5.

2. Identification of fuzzy model

Process modelling is a problem particularly significant for the implementation and the development of controlled systems. In this section it is assumed that fuzzy systems are multi input single output $Y: U \rightarrow V$ where the input space is $U = u_1 u_2 \dots u_N$ and the output space is V .

Consider a system which is described in the discrete time by $y(k+1) = f(z(k))$

where the regression vector

$$z(k) = [u_1(k), \dots, u_r(k), q_1(k), \dots, q_p(k), y_1(k), \dots, y_m(k)] \quad (2)$$

with r process input U , p measurable disturbance q , and m process inputs y . the unknown function $f(\cdot)$ is approximated by using Takagi-Sugeno type fuzzy model, represented by a collection of fuzzy if-then rules:

$$R_l: \text{if } z_1 \text{ is } A_{l1} \text{ and } \dots \text{if } z_{nz} \text{ is } A_{lnz} \quad (3)$$

$$\text{then } y_l(k+1) = a_{l0} + a_{l1}z_1 + \dots + a_{lnz}z_{nz}$$

with $nz = r + m + p$ and $A_{li} \in U$ are linguistic terms characterized by fuzzy membership functions $\mu_l(z)$.

l is the index of rules ($l=1,2,\dots,M$)

$$\mu_l(z) = \exp\left(-\frac{(z_1 + c_{l1})^2}{2\sigma_{l1}^2}\right) + \dots + \exp\left(-\frac{(z_{nz} + c_{lnz})^2}{2\sigma_{lnz}^2}\right) \quad (4)$$



where $\mu_l(\cdot)$ is the degree of fulfilment of rules l , the centers c_l and the standard derivations σ_l are the parameters of the Gaussian membership function.

The output of TS model will be calculated with the following equation.[zeng 1994]

$$y(k+1) = \frac{\sum_{l=1}^M \mu_l(z(k)) y_l(k+1)}{\sum_{l=1}^M \mu_l(z(k))} \quad (5)$$

$$\text{or } y(k+1) = \sum_{l=1}^M \varphi_l(z, c_l, \sigma_l) y_l(k+1)$$

where $\varphi_l(z, c_l, \sigma_l)$ is the validation function for the Gaussian membership functions with centers c_l and standard derivations σ_l defined as

$$\sigma_l(z, c_l, \sigma_l) = \frac{\mu_l(z(k))}{\sum_{i=1}^M \mu_i(z(k))} \quad (6)$$

3. Greenhouse climate model

The greenhouse climate model describes the dynamic behaviour of the stated variables by use of differential equations for the air temperature, humidity, CO₂ concentration etc. these differential equation are results of combination of the various physical processes involving heat and mass transfer taking place in the greenhouse and from the greenhouse to the outside air Figure.1.a:

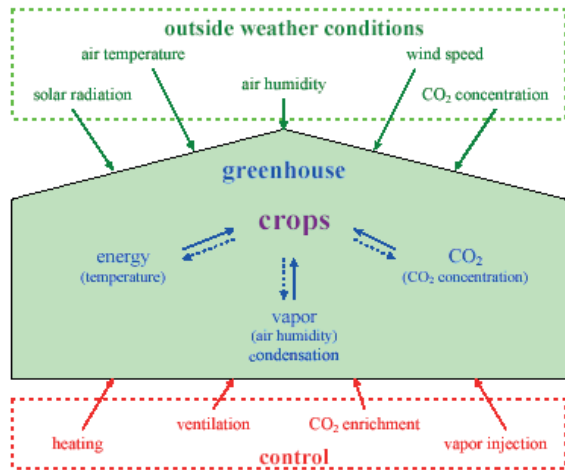


Figure 1.a: Scheme of greenhouse climate model

The important number of variables, (references, perturbations and commands) and the complexity of phenomena (biologic, weather, evolution of the plants...), make that we have a system multivariable, nonlinear and non stationary. Moreover, the perturbations, as the wind velocity and the global radiation, can sometimes have a power more raised than the command such the heating.

For these reasons, we thus preferred to apply a multimodal based on fuzzy logic and taken into account all the variables of which we dispose Figure.1.b:

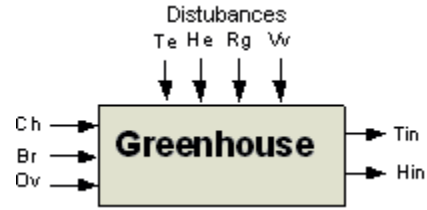


Figure 1.b: Input/output diagram of a greenhouse

where, T_i and H_i are respectively temperature and relative humidity of the internal air, the perturbation variables are T_e (external temperature), H_e (external humidity), R_g (solar radiation), V_r (wind velocity) and the input variable are Ch (heating), Br (moistening) and Ov (roofing)

To simplify the complexity of the considered system, greenhouse, we have proposed to decompose the MIMO system into a MISO. By this decomposition, the MISO systems are represented by compact TS model and convert a nonlinear problem into linear one.

The TS model is defined by the rules which are linear conclusions of the systems outputs, for example for the rule j :

$$\text{if } o_v(k), ch(k), \dots, R_d(k) \text{ is } V_j \text{ then } T_{ij}(k+1) = a_{j1}o_v(k) + a_{j2}(k)ch(k) + \dots + a_{j9}R_d(k) \quad (7)$$

$$\text{if } o_v(k), ch(k), \dots, R_d(k) \text{ is } W_l \text{ then } H_{il}(k+1) = b_{l1}o_v(k) + b_{l2}(k)ch(k) + \dots + b_{l9}R_d(k) \quad (8)$$

with

$$\hat{\theta}_1 = [a_{j1}, a_{j2}(k), \dots, a_{j9}] \text{ and } \hat{\theta}_2 = [b_{l1}, b_{l2}(k), \dots, b_{l9}]$$

are respectively model parameters for the temperature and humidity for the rule j . V_j and W_l are membership functions centers which are defined later. In this work we are interesting on a nonlinear with time variant behaviour. There for, an on line adaptation is necessary to obtain a good model able to describe the process in a large operating points to be used in a schema of adaptation control [3].

The rule conclusion is a linear model (3) calculated through a last squares approximation method, considering the input data and the associated output. The estimated parameters are chosen such they minimize the criteria:

$$J(\theta_i(k)) = \sum_{j=1}^R h_i(k) \cdot (y_i - z^T \hat{\theta}_i)^T (y_i - z^T \hat{\theta}_i) \quad (9)$$

where y_i is the output

$$\text{and } h_i(k) = \frac{\mu_i(z(k))}{\sum_{l=1}^M \mu_l(z(k))} \quad (i=1,2).$$



μ_i is the membership function of the data $Z(k)$ at the rule j .

We put $H_i = \text{diag}(h_1(k), \dots, h_R(k))$ (10)

The parameter vector $\hat{\theta}_1$ and $\hat{\theta}_2$ are updated online, by consideration that only the rules consequence are adapted for each local model by a recursive of the weighted least squares algorithm with forgetting factor λ :

$$\hat{\theta}_i(k) = \hat{\theta}_i(k-1) + \delta_i(k)(y_i(k) - z^T(k)\hat{\theta}_i(k-1)) \quad (11)$$

$$\delta_i = \frac{P_i(k-1)z(k)}{z^T(k)P_i(k-1)z(k) + \frac{\lambda}{p_i(k)}} \quad (12)$$

$$p_i = \frac{1}{\lambda}[I - \delta_i z^T(k)]p_i(k-1) \quad (13)$$

where $h_i(\cdot)$ is the weighting of actual data with the rule activation and p_i is a matrix of the adaptation gain

4. Fuzzy clustering algorithm

The objective of clustering methods is to perform a partition of the collection of elements into c data sets, where the number c of clusters is defined online and depend of the state of day. In the generality of the situations, these elements are vectors of points in a space with a norm and distance measured and its results is a set of cluster of discrete points.

The objective of clustering is to partition a data set Z into c clusters. Through clustering, the fuzzy partition vector $\mu(z(k)) = [\mu_j(z(k))]_{c \times 1}$ is obtained, whose elements

μ_k represent the degree of membership of the observation $z(k)$ in the cluster v_j ($j=1,2,\dots,c$).

The partition should find a vector of clusters center, the number of clusters and a partition vector $\mu(z(k))$. This procedure is composed into four steps:

Step 1. Initialization

For a set of point Z , we calculate the distance between $z(i)$ and $z(j)$.

$$D_{ij}^2 = (z(i) - z(j))^T (z(i) - z(j)) \quad (14)$$

we determine the data point which done the maximum distance.

$$D_{\max}^2 = \max_{1 \leq i, j \leq N} (D_{ij}^2) \\ = (\bar{z}(i) - \bar{z}(j))^T (\bar{z}(i) - \bar{z}(j)) \quad (15)$$

where N is the number of data.

we initialize the centers of the two first clusters v_1 and v_2 with $V_1 = \bar{z}(i)$, $V_2 = \bar{z}(j)$ and $c = 2$

Step 2. compare

$$\max_{1 \leq i \leq c} (\|V_i - z(k)\|) \text{ to } \varepsilon$$

If $\max_{1 \leq i \leq c} (\|V_i - z(k)\|) \geq \varepsilon$ $c = c + 1$ and $V_c = z(k)$

Otherwise compute the c , mean vectors.

Step 3. compute the new partition vector μ and calculate

$$\hat{\theta}_1 \text{ and } \hat{\theta}_2$$

Step 4. compute the output of system, go to step 2 for future measure

In the simulation section, this strategy is applied to break the greenhouse fuzzy climate temperature and humidity.

5. Simulation results

In this section the results achieved with the proposed greenhouse climate strategies are presented. The identification of both models was done by using input-output data previously collected.

In figure 2 and 3, we present the results obtained from a simulation compared during a test period. These curves show a good agreement between measured data and the models outputs.

Figure 4 shows the evolution of parameters θ_1 and θ_2

6. Conclusion

This paper proposes a study of the application of fuzzy clustering to the identification of Takagi-Sugeno (TS) fuzzy models. These local models correspond to the different rules generated automatically which have variable consequent linear parameters in contrast to the common approach using fixed consequent linear parameters.

The performance of the proposed modelling technique was demonstrated and successfully applied to real problems such as modelling of physical and biological process. The fuzzy clustering has been tested to split the inside greenhouse air temperature and humidity.

7. References

- [1] I. Laribi Maatoug, R.Mhiri, An Explicit Solution for the Optimal Control of Greenhouse Temperature relying on Embedded System, ICGST-ACSE, Volume 8, Issue I, ISSN: 1687-4811, 2004
- [2] J-F Balmat, F. Lafont, Multi-model architecture supervised by Kohonen map, International Conference on Electronic Sciences, Information Technology and Telecommunication (SETIT), Mahdia, Tunisia, 6:17-21, 2003.
- [3] A. Fink, M. Fischer, O. Nelles, Supervision of Nonlinear Adaptive Controllers Based on Fuzzy Models, Control Engineering, 8: 1093-1105, 2000.
- [4] O. Nelles, A. Fink, R. Isermann, Local Linear Model Trees (LOLIMOT) Toolbox for Nonlinear System Identification, 12th FAC Symposium on System Identification (SYSID), Santa Barbara, USA, 2000.
- [5] J.S.R. Jang, ANFIS: Adaptive-network based fuzzy inference system, IEEE Transactions on Systems, Man and Cybernetics, 23(3): 665-685, 1993.
- [6] L. Ljung, System identification-theory for the user Englewood cliffs, NJ: Prentice-Hall, 1987.
- [7] M. Sugeno, G.T. Kang Structure identification of fuzzy model, Fuzzy Sets and Systems, 28: 15-33, 1987.



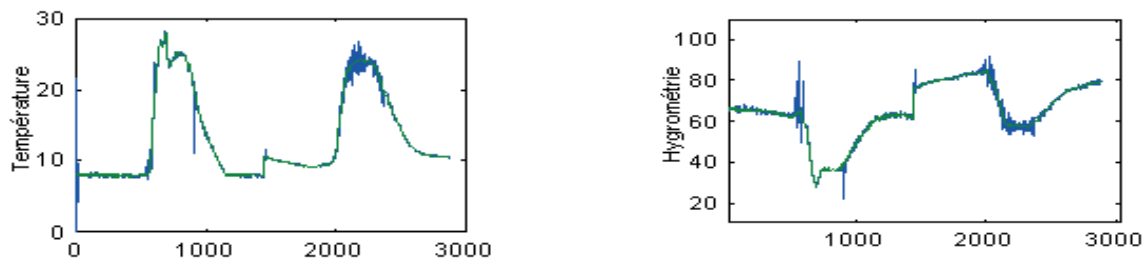


Figure 2. Comparison of the process output and the fuzzy model output with parameter's adaptation

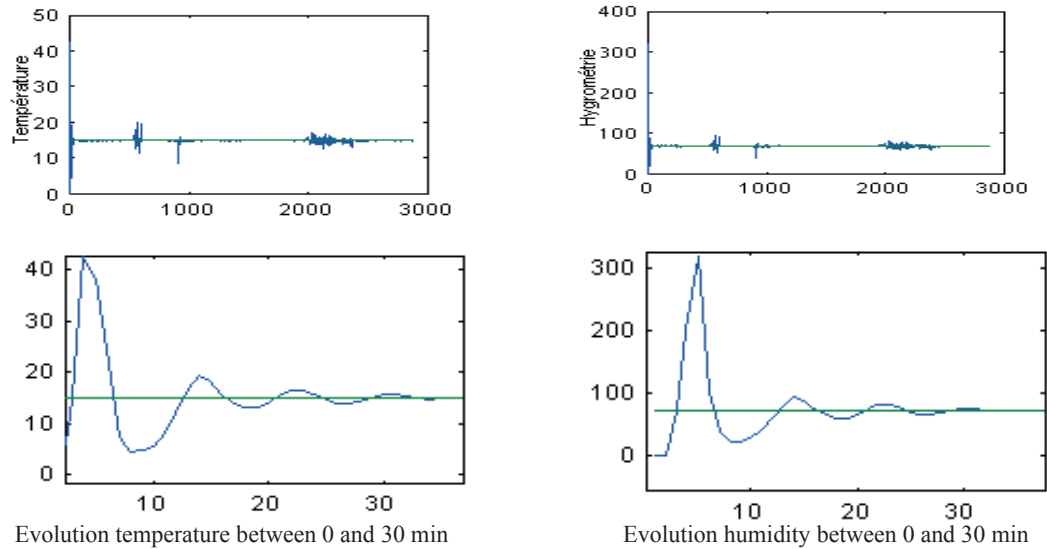


Figure 3. Comparison of the process output and the fuzzy model output with parameter's adaptation. (by considering consign $T_{ic}=20^{\circ}\text{C}$, and $H_{ic}=70\%$)

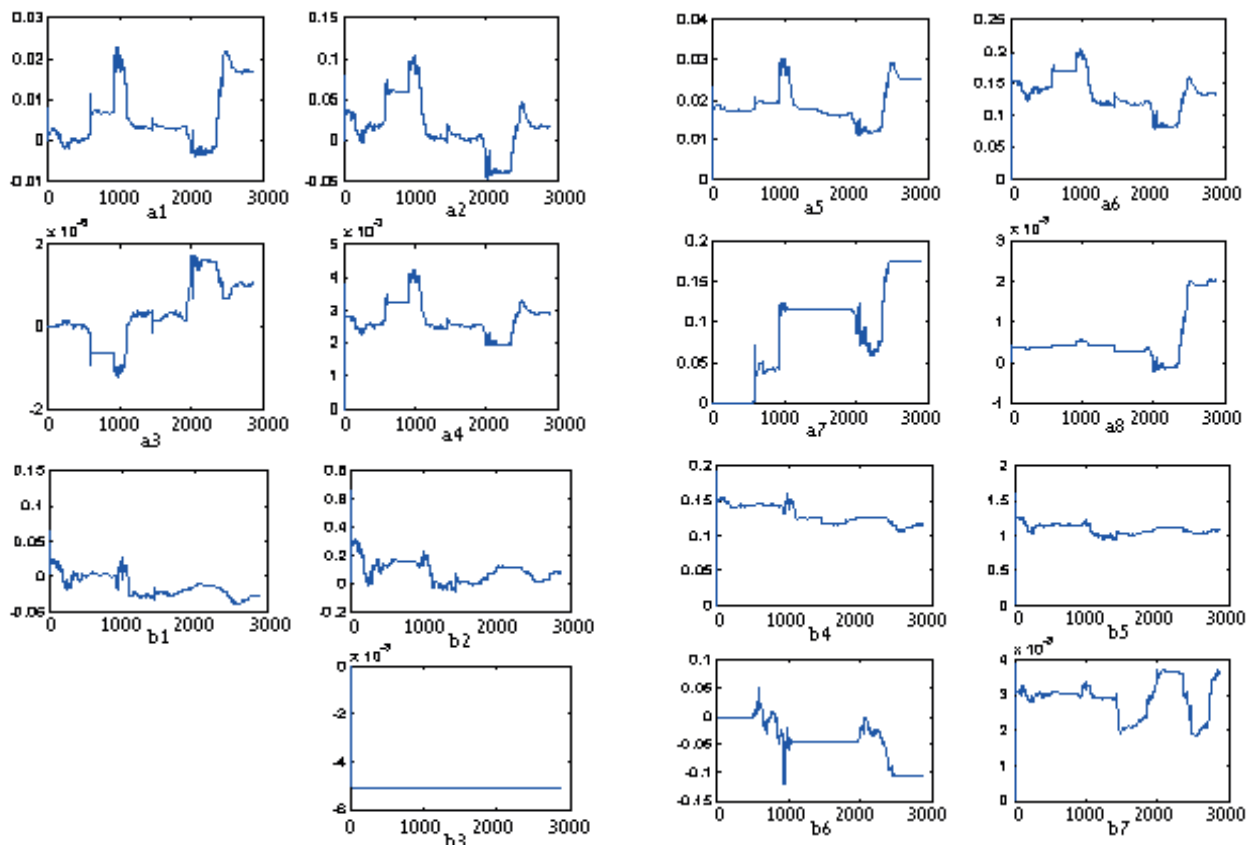


Figure 4. Evolution of parameters vectors



Biographies:



Ahmed Errahmani, received his Master's degree in 2004 from the University Sidi Mohamed Ben Abdellah, Faculty of Sciences, Fèz Morocco. He is pursuing his Ph. D. degree. His research areas include fuzzy control of non-linear systems.



Ismail Boumhidi is a Professor of electronics at the Faculty of Sciences, Fez Morocco. He received from the University Sidi Mohamed ben Abdellah Faculty of sciences his "Doctorat de 3ième cycle" degree in 1994 and "Doctorat d'Etat" degree in 1999.



Majid Benyakhlef, graduated from the University of Mohamed V, Faculty of science Rabat, He received a Ph. D. degree in 2006 from the University Sidi Mohamed Ben Abdellah Faculty of sciences, Fez. He has been a Professor

assistant of Informatique and Automatic control at the Faculty Polydisciplinaire of Taza. Currently, his research interests include decentralized robust control, fuzzy control and adaptive control of large scale systems.







Modeling and Approach for Vendor Managed Inventory Cyclic IRP

HONG-ZHEN ZHENG, DIAN-HUI CHU, DE-CHEN ZHAN and XIAO-FEI XU

Department of Computer Science & Technology, Harbin Institute of Technology, Weihai, China, 264209.

Emails: hithongzhen@163.com

Abstract

This paper presents a practical modeling and solution approach for the cyclic inventory routing under constant customer demand rates. The solution approach presented in this paper assumes a given vehicle type. The heuristic solution approach is well capable of finding the appropriate cost trade-off under varying circumstances. Furthermore, when fleet sizing is not considered, the heuristic outperforms an existing heuristic in finding the two way trade-off between distribution and inventory costs. The objective of this inventory routing problem (IRP) is to determine a distribution plan that minimizes average distribution and inventory costs without causing any stock-out at the customers. Deterministic constant customer demand rates are assumed and therefore, a long-term cyclical approach is adopted, integrating fleet sizing, vehicle routing, and inventory management. Further, realistic side-constraints such as limited storage capacities, driving time restrictions and constant replenishment intervals are taken into account. Computational experiments show that our column generation based heuristic solution approach is well capable of finding the appropriate cost trade-off under varying circumstances.

Keywords: IRP, VMI, Supply chain, distribution and inventory costs

1.Introduction

The problem of integrating inventory and distribution decisions has been approached in different ways depending on inventory policies used at the customers, service level restrictions, and the time horizon considered. Integrating decisions related to different stages allows trade-offs to be examined and a better overall performance to be achieved. Over the last decades, both academics and practitioners have become aware of the importance of collaboration between the different stages in a supply chain. Integrating decisions related to different stages allows trade-offs to be examined and a better overall

performance to be achieved. One particular example of supply chain collaboration is the concept of vendor managed inventory (VMI), encountered in distribution planning. Under a VMI-strategy, customers make their inventory data available to the distributor, and leave the responsibility of deciding when and in what quantities they are replenished to the distributor. The distributor thus has more freedom in designing efficient vehicle routes. Benjaafar, Saif [1] determine an optimal demand allocation and optimal inventory levels at each location so that the sum of transportation, inventory, and backorder costs is minimized. Chen, Yee Ming and Lin, Chun-Ta [2] solve the multi-product multi-period inventory routing problem with stochastic demand. Computational results demonstrate the importance of this approach not only to risk-averse decision makers, but also to maximize the net present value at an acceptable service level. As a result, an optimal portfolio (R, s, S) system of product group can be generated to maximize the net present value under an acceptable service level in a given planning horizon. These seminal papers have incited a body of literature on inventory routing, most of them considering stochastic demands and short time horizons. Sun, Mao and Li, Wen-Nian^[3] give An inventory routing problem for a two-echelon distribution system consisted of one supplier (or distribution center) and many retailers based on deterministic demand under the mode of traditional retailer management inventory was studied. Raa, Birger and Aghezzaf, El-Houssaine [4] discuss the challenging optimization problem that arises in this context, known as the inventory routing problem. The objective of this IRP problem is to determine a distribution plan that minimizes average distribution and inventory costs without causing any stock-out at the customers. Deterministic constant customer demand rates are assumed and therefore, a long-term cyclical approach is adopted, integrating fleet sizing, vehicle routing, and inventory management. Savelsbergh, Martin and Song, Jin-Hwa [5] develop an integer programming based optimization algorithm capable of solving small to medium size instances. This optimization



algorithm is embedded in local search procedure to improve solutions produced by a randomized greedy heuristic. We demonstrate the effectiveness of this approach in an extensive computational study.

The cyclic inventory routing problem has to be analyzed from a long-term perspective, in which the vehicle fleet is variable. Therefore, decisions on the vehicle fleet size have to be incorporated and a fixed vehicle cost has to be taken into account. However, most of the above mentioned papers use single routes per vehicle and assume that enough vehicles are available. In other words, vehicle fleet sizing decisions are not considered and the assignment of routes to vehicles is not taken into account.

Raa, Birger and Aghezzaf, El-Houssaine [6] proposes a practical solution approach for the challenging optimization problem of minimizing overall costs in an integrated distribution and inventory control system. Constant customer demand rates are assumed and therefore a long-term, cyclic planning approach is adopted.

Zachariadis, Emmanouil E and Tarantilis, Christos D [7]. studies an inventory routing model which integrates two important components of the supply chain: transportation logistics and inventory control. The aim of the problem is to determine the timing and size of the replenishment services together with the vehicle routes, so that the total transportation and inventory holding cost of the system is minimized. In methodological terms, they propose a solution approach applying two innovative local search operators for jointly dealing with the inventory and routing aspects of the examined problem, and Tabu Search for further reducing the transportation costs. The proposed algorithmic framework was tested on a set of new benchmark instances of various scales. It produced satisfactory results both in terms of effectiveness and robustness.

The capacity constraints result in a restriction on the time between consecutive replenishments of a customer, i.e. in a maximal cycle time. On the other hand, there is also a minimal cycle time, a minimal amount of time between consecutive deliveries because the vehicle needs some time to drive to other customers and to the depot before it can come back. However, this minimal cycle time is not found in any of the above mentioned papers.

Shen, Sheng-Yuan; Honda, Masakazu [8] focus on developing an integrated replenishment and routing plan that takes into account lateral transfers of both vehicles and inventory for a three-echelon supply chain system including a single plant, multiple distribution centers and multiple retailers. A mixed integer programming model to the overall system is formulated first, and then an optimization-based heuristic consisting of three major components is proposed. Aghezzaf, E.-H [9] discusses the case where customer demand rates and travel times are stochastic but stationary, and proposes a version of the inventory routing optimization model that

generates optimal robust distribution plans. The approach proposed to obtain and deploy these robust plans combines optimization and Monte Carlo simulation. Optimization is used to determine the robust distribution plan and simulation is used to fine-tune the plan's critical parameters such as replenishment cycle times and safety stock levels.

The problem at hand is thus the cyclic inventory routing problem (CIRP), in which a vehicle fleet and a cyclic distribution scheme for the selected vehicles have to be designed such that the total cost rate is minimized. This paper extends earlier work^[8,9] by presenting a practical modeling and solution approach for cyclic inventory routing problems that takes into account driving time restrictions. The remainder of this paper is organized as follows.

Section 2 presents the modeling approach. Section 3 describes the solution approach. Section 4 gives Comparison to another heuristic. Section 5 provides conclusions and directions for future research.

2. Modeling Approach

Under the VMI-strategy, the distributor is faced with the problem of integrating its vehicle routing decisions with the inventory management of the customers. This integrated problem is known in literature as the inventory routing problem (IRP).

In the long-term, the vehicle fleet is variable and fleet sizing has to be integrated with routing. Therefore, the routing concept is generalized such that a single vehicle can make multiple tours with different frequencies. Solving the cyclic inventory routing problem with constant demand rates is highly complex. It can be considered as a combination of the following inter-related and sub problems:

- 1) Partitioning and assigning customers to a number of vehicles.
- 2) Further partitioning of the subset of customers, assigned to a vehicle, into sub-subsets that will each be replenished in a separate tour.
- 3) Constructing for every customer sub subset the shortest depot-to-depot tour that visits all customers in the sub subset.
- 4) Determining for each vehicle an appropriate cycle time and frequencies for its tours.
- 5) Constructing for each distribution pattern a delivery schedule to check feasibility and determine the cost rate.

Consider a vehicle replenishing a subset of customers S . The vehicle makes a distribution pattern with a cycle time of T days, consisting of n different tours, each visiting one of the disjoint customer subsets $S_i (i \in 1, \dots, n)$. For each tour i , a (relative) frequency f_i is determined, meaning that the tour is made f_i times during one cycle. Since the number of days between consecutive deliveries to a customer has to be constant, the number of days between consecutive executions of a tour also has to be constant. Furthermore, the driving time is restricted to H hours



per day. As a result, the number of days in one cycle, i.e. the cycle time T of the distribution pattern, has to be an integer multiple of all tour frequencies f_i . The least common multiple of all f_i thus defines a base cycle time of D days.

One execution of tour i takes $T_{TSP(S_i^+)}$ hours for making the TSP-tour through the set S_i^+ , plus $\sum_{j \in S_i^+} t_j$ hours for delays at all locations in S_i^+ , where t_j stands for the unloading time at customer $j \in S_i$, and Note that this tour duration cannot exceed H hours. A distribution pattern cannot be restarted before the vehicle has made f_i times each of its tours i . Knowing that only H hours of driving are possible per day, and that the number of days in a cycle has to be an integer multiple of D days, this leads to the following lower bound $T_{\min}$ for the distribution pattern cycle time T :

$$T_{\min} = D \left\lceil \frac{1}{H \cdot D} \sum_{i=1}^n f_i (T_{TSP(S_i^+)} + \sum_{j \in S_i^+} t_j) \right\rceil \quad (1)$$

The maximal quantity that the vehicle can deliver to the customers in the tour is thus f_i times the vehicle capacity C . To avoid stock-outs, the vehicle has to return to its customers before they have consumed this full truckload. Therefore, T/f_i , the time between consecutive deliveries, cannot be larger than the vehicle capacity divided by the cumulative demand rate of all customers in the tour: $\frac{T}{f_i} \leq \frac{C}{\sum_{j \in S_i} d_j}$, with

d_j expressed in units per day. Similarly, the limited storage capacity of the customer j , denoted by C_j .

Taking into account the base cycle time of D days, the upper bound $T_{\max}$ on the distribution pattern cycle time T is as follows:

$$T_{\max} = D \left\lceil \frac{1}{D} \min_{i \in 1 \dots n} \left(\frac{C f_i}{\sum_{j \in S} d_j} \right), \min_{j \in S} \frac{f_i f_j}{d_j} \right\rceil \quad (2)$$

Obviously, a distribution pattern is only feasible if the lower bound is not greater than the upper bound on the cycle time: $T_{\min} \leq T_{\max}$.

The cost rate R of a distribution pattern consists of the following components:

- 1) The fixed vehicle cost of α \$ per day.
- 2) The variable transportation cost of $\sum_{i=1}^n f_i R_{TSP(S_i^+)}$ \$ per day.
- 3) The fixed vehicle loading and dispatching cost of $\sum_{i=1}^n f_i \beta_i$ \$ per cycle.
- 4) The fixed unloading cost at the customers of

$$\sum_{i=1}^n \sum_{j \in S_i} f_i \beta_j \text{ $ per cycle.}$$

The stock holding cost at the customers. The quantity delivered to customer $j \in S_i$, denoted by q_j , covers

demand for $\frac{T}{C_i}$ days, so $q_j = d_j \frac{T}{C_i}$.

The total cost rate of the distribution pattern replenishing the set of customers S is given in the following formula:

$$R = \alpha + \frac{1}{T} \left(\sum_{i=1}^n f_i (R_{TSP(S_i^+)} + \sum_{j \in S_i^+} \beta_j) \right) + T \left(\sum_{i=1}^n \sum_{j \in S_i} \frac{\gamma_j d_j}{2 f_i} \right) \quad (3)$$

This cost rate varies with the cycle time and with the frequencies f_i . Thus, for every combination of frequencies, there is a theoretical optimal cycle time, for which the cost rate is minimal. This occurs when holding costs at the customers are balanced with the sum of transportation costs and fixed tour costs (components (2)-(4)). This is a generalization of the well-known Economic Order Quantity model, and therefore, this optimal cycle time is called the EOQ cycle time and denoted T_{EOQ} :

$$T_{EOQ} = \sqrt{\frac{\sum_{i=1}^n f_i (R_{TSP(S_i^+)} + \sum_{j \in S_i^+} \beta_j)}{\sum_{i=1}^n \sum_{j \in S_i} \frac{\gamma_j d_j}{2 f_i}}} \quad (4)$$

Once frequencies f_i and a cycle time T of a certain number of days are selected, each execution of every tour in the distribution pattern is assigned to a particular day in the cycle such that (1) the number of days between consecutive executions of the same tour is constant, (2) the vehicle drives at most H hours per day. Because of these two constraints, it is unlikely that a vehicle drives around the whole time and thus idle time needs to be introduced in the vehicle's cyclic schedule.

3. Solution Approach

As the modeling approach presented in Section 2, this section discusses a solution approach that tries to find good-quality solutions that achieve good trade-offs between the different cost components. The solution approach presented here extends previous work^[8,9] by considering the more general routing concept of distribution patterns and taking into account driving time restrictions.

Here, an improvement heuristic is proposed that can be applied to an existing solution at any time to improve the solution quality. The improvement heuristic consists of removing and re-inserting a customer. Re-inserting a customer into the solution is similar to inserting a customer in the insertion heuristic. The customer is inserted into the existing distribution patterns of the solution, both in a separate tour and in the existing tours, and the cheapest alternative is kept. If a customer ends up in the same



position as before, the solution is restored and no improvement is found. If the customer ends up in a different position, the solution has improved. The order in which the customers are considered for removal and re-insertion is also determined by the customer priority.

We need to find a collection of distribution patterns, a partition of the set of customers S into disjoint subsets, each covered by a separate distribution pattern, needs to be found, such that the sum of cost rates of the distribution patterns is minimal. If we let Dis-Pat denote the collection of all possible distribution patterns, this problem is formulated as follows:

$$\begin{aligned} \min \quad & TCR = \sum_{p \in DP} R^p X^p \\ \text{S.T.} \quad & \begin{cases} \sum_{p \in DP} Y_i^p X^p = 1 & \forall i \in S \\ X^p \in \{0,1\} & \forall p \in \text{Dis-Pat} \end{cases} \end{aligned}$$

Where R^p is the cost rate of distribution pattern $p \in \text{Dis-Pat}$, and Y_i^p is the binary matrix stating whether distribution pattern $p \in \text{Dis-Pat}$ covers customer $i \in S$ or not. The binary variable X^p indicates whether distribution pattern $p \in \text{Dis-Pat}$ is selected or not.

The set Dis-Pat of possible distribution patterns, i.e. the number of columns in problem (MP), is infinitely large. Therefore, we need an efficient way of producing only the most promising distribution patterns in Dis-Pat, such that a near-optimal solution for the problem is quickly reached.

Column generation is an appropriate framework to this end. We propose column generation procedure consists of the following steps:

Step1. The set of distribution patterns Dis-Pat is initialized with a separate distribution pattern for each customer and the initial matrix Y is the identity matrix.

Step2. The linear programming relaxation of the master problem (MP) is solved.

Step3. Constraint (5) gives a dual price for each of the customers, $p_i, \forall i \in S$ (Generate the basic distribution patterns, each serving a single customer and use their cost rates as customer priorities p_i . Sort the customers according to this priority.). These dual prices are used as customer priorities.

Step4. If the customer priorities are the same as in the previous iteration, they are randomized by multiplying them with a uniformly generated random number between 0 and 10. If this is the sixth time that the customer priorities are randomized, the process goes to Step 5.

step (1) Perform the savings heuristic to construct a solution and apply the improvement heuristic to it.

step (2) Perform the insertion heuristic to construct a solution and apply the improvement heuristic to it.

If new distribution patterns are constructed in steps (1)

and (2), they are added to the set DIS-PAT and the corresponding columns are added to the matrix Y . The process then returns to Step 2.

Step5. The master problem (MP) is solved to integrality $X^p \in \{0,1\}$ to provide the final solution.

In traditional column generation schemes, this means that the LP-optimum is found and the column generation is finished. However, we are using heuristics for the column generating sub problem, such that columns with a negative reduced cost may not be found even though they do exist, leading to a premature ending of the column generation process.

Another difference with traditional column generation is that we add multiple columns per iteration. In fact, all distribution patterns that the heuristics in the column generating phase encounter, are added as new columns in the master problem. For large problem instances however, distribution patterns are only added to the master problem if their reduced cost rate is negative. This is done in order to limit the number of columns and thus the CPU-time in the Step 5, where a branch-and-bound procedure is needed to solve the master problem to integrality.

4. Comparison to another heuristic

This section illustrates the value of our solution approach which is compared to the solution approach of Viswanathan and Mathur [10].

As in most papers found in the literature on cyclic inventory routing, a fixed vehicle cost is not considered in the cost structure of Viswanathan and Mathur. They developed a heuristic that generates a so-called stationary nested joint replenishment policy (SNJRP). They call a policy stationary if replenishments are made at equally spaced points in time. A nested policy means that if the replenishment interval of a given customer is larger than that of another customer served by the same vehicle, the former is a multiple of the latter.

Thus, the nestedness corresponds to our delivery frequencies, because not all customers visited by the same vehicle have the same replenishment interval.

As a result, the assignment of tours to vehicles is not taken into account and the assumption is made that there is a separate vehicle for every tour. For the cycle times, they only use vehicle capacity as a constraining element.

Compared to our model, the restrictions following from (1) traveling, loading and unloading times, and (2) limited customer storage capacities are discarded. A minimal cycle time for the tours is thus not considered. To compare our heuristic method to that of Viswanathan and Mathur, the fixed vehicle cost has to be discarded and the minimal cycle time T_{min} ignored.

To evaluate the solution approach presented in Section3, a number of tests were run on problem instances with varying characteristics. The test instances are generated according to a 10×2^3



Factorial Design, in which the following three factors are considered.

The first factor is the customer storage capacity restriction (CCAP), with level 'No' or 'Yes' indicating the inclusion of the restriction or not. The second factor is the holding cost, which is either 80 or 8 \$ per unit per day. This holding cost rate is assumed to be the same for all customers. The third and last factor is the number of customers (NR). The two levels of this factor are [50-90] and [100-150]. This factor is a randomized factor, meaning that instead of considering two fixed values for the factor, values are generated randomly in two distinct intervals. The number of customers is thus either between 30 and 70 or between 80 and 120.

Comparing our heuristic (Dis-Pat) to SNJRH as Table 1.

Table 1 Comparing our heuristic (Dis-Pat) to SNJRH

HC	NR	SNJRH	Dis-Pat	Δ
100c	[50-90]	1420.7	1289.8	-9.2
100c	[100-150]	3089.3	2842.4	-8.0
10c	[50-90]	721.4	694.4	-3.7
10c	[100-150]	1592.2	1538.1	-3.4
Average		1705.9	1584.2	-6.1

The results shows g that our solution method using distribution patterns (Dis-Pat) and those obtained with the stationary nested joint replenishment heuristic (SNJRH). Our tests show that this approach is more effective than directly solving the problem heuristically.

For all problem instances, solutions are found that are cheaper than those proposed by Viswanathan and Mathur. On average, there is a cost decrease of no less than 6.1%. This is mostly due to the more general routing concept that we are using. These results show that allowing vehicles to make multiple tours gives the opportunity to use vehicle capacity much more efficiently and find much better cost trade-offs, even without considering fixed vehicle costs. Computational experiments show that our column generation based heuristic solution approach is well capable of finding the appropriate cost trade-off under varying circumstances.

5. Conclusions

In this paper, we present a practical modeling and solution approach for the cyclic inventory routing under constant customer demand rates. The proposed long-term approach is the first to find three-way cost trade-offs between vehicle fleet size costs and distribution costs and inventory costs. Furthermore, when fleet sizing is not considered, the heuristic outperforms an existing heuristic in finding the two way trade-off between distribution and inventory costs. We assumes a given vehicle type in our solution approach. Yet, it can still be applied in cases where the fleet contains different vehicle types (with

different capacities and costs). Actually, if the fleet is made of vehicles with different capacities and operating costs, then the fourth step in the column generation framework must be re-run for each vehicle capacity. The mater problem will then select the best distribution pattern and thus the appropriate vehicle. This of course will increase the computational burden of the approach. Also, some other simplifying assumptions, including not allowing split delivery and imposing a constant time between consecutive deliveries may be relaxed, offering more freedom to obtain possibly even better solutions. However, this will probably increase the complexity of the resulting solutions which may, in turn, decrease their applicability in practice.

The cyclic approach brings stability and predictability to the planning. On the one hand, this may reduce the nervousness and thus the customer demand variability and the resulting safety stocks. Thus, quantifying this variability reduction is an interesting avenue for further research. On the other hand, demand variability will not disappear completely, so it is worthwhile to investigate how the approach can be extended to explicitly take some demand variability into account.

6. Acknowledgements

This paper is supported by Shandong Province Natural scientific research Foundation (2007ZR A10003) and Shandong Province Scientific and technological projects (2008GG10 004010) .

7. References

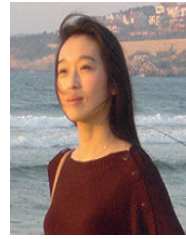
- [1] Benjaafar, Saif; Li, Yanzhi; Xu, Dongsheng; Elhedhli, Samir. Demand allocation in systems with multiple inventory locations and multiple demand sources. Source: Manufacturing and Service Operations Management, v 10, n 1, p 43-60, 2008.
- [2] Chen, Yee Ming ; Lin, Chun-Ta. A coordinated approach to hedge the risks in stochastic inventory-routing problem source: Computers and Industrial Engineering, v 56, n 3, p 1095-1112, April 2009.
- [3] Sun, Mao; Li, Wen-Nian; Zhou, Yong-Wu. Deterministic operational inventory routing problem Source: Jisuanji Jicheng Zhizao Xitong/Computer Integrated Manufacturing Systems, CIMS, v 14, n 2, p 341-348, February 2008 Language: Chinese.
- [4] Raa, Birger; Aghezzaf, El-Houssaine. A practical solution approach for the cyclic



inventory routing problem Source: European Journal of Operational Research, v 192, n 2, p 429-441, January 16, 2009.

- [5] Savelsbergh, Martin; Song, Jin-Hwa. An optimization algorithm for the inventory routing problem with continuous moves Source: Computers and Operations Research, v 35, n 7, p 2266-2282, July 2008, Selected Papers Presented at the ECCO'04 European Conference on Combinatorial Optimization
- [6] Raa, Birger; Aghezzaf, El-Houssaine. Designing distribution patterns for long-term inventory routing with constant demand rates Source: International Journal of Production Economics, v 112, n 1, p 255-263, March 2008.
- [7] Zachariadis, Emmanouil E.; Tarantilis, Christos D.; Kiranoudis, Chris T. An integrated local search method for inventory and routing decisions. Source: Expert Systems with Applications, v 36, n 7, p 10239-10248, September 2009.
- [8] Shen, Sheng-Yuan; Honda, Masakazu. Incorporating lateral transfers of vehicles and inventory into an integrated replenishment and routing plan for a three-echelon supply chain Source: Computers and Industrial Engineering, v 56, n 2, p 754-775, March 2009.
- [9] Aghezzaf, E.-H. Robust distribution planning for supplier-managed inventory agreements when demand rates and travel times are stationary Source: Journal of the Operational Research Society, v 59, n 8, p 1055-1065, August 2008.
- [10] Viswanathan, S., Mathur, K., Integrating routing and inventory decisions in one-warehouse multi-retailer multi-product distribution systems. Management Science 43 (3), 294-312.

Biographies

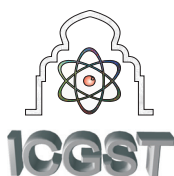


Zheng Hongzhen, PhD in Computer Science, Professor. Prof. Zheng is the dean of the Department of Computer Science. In recent years, she has published more than 40 papers including 13 SCI/EI papers and 4 international journal papers. Her research areas are supply chain management, data-mining and business intelligence. She is in charge of many projects including 863 projects and science and technology projects in Shandong Province. Email: hitongzhen@163.com.



Chu Dianhui, Master in Computer Science, Associate Professor. Prof. His research areas are ERP, supply chain management, logistics Service management. Email: chudianhui@vip.sina.com





Decentralized Fuzzy Control Applied to a Greenhouse

A. Errahmani*, M. Benyakhlef** and I. Boumhidi*

* LESSI, Département de physique, Faculté des Sciences Dhar El Mehraz.

BP 1796 Atlas Fez 30 000 MOROCCO

** Faculté Polydisciplinaire Taza

aerrahmani@menara.ma*, mbenyakhlef@netcourrier.com**

Abstract

This paper investigates the use of fuzzy method as a tool for model identification and control of a nonlinear and multivariable system (greenhouse) when measurement data is available. The simulation of the internal climate is achieved by a linear model whose coefficients are obtained using the fuzzy clustering method. The use of fuzzy logic decentralized controller for the regulation of climate variables represents powerful way to economise the energy and reduce the complexity of the controller. Simulation results show that the proposed strategy is applied successfully to control the internal climate of greenhouse system.

Keywords: *Decentralized Systems, Fuzzy control, Greenhouse.*

1. Introduction

The control of greenhouse climate, in order to improve the development of a specific cultivation and to minimize the production costs, is becoming increasingly important for the growers [9], [12]. The production under greenhouse can contribute efficiently to increase the productivity. To cover these needs it is therefore necessary to perfect the air-conditioning of the greenhouse in order to maintain the culture in the conditions that are compatible with the agriculturist's agronomic and the economic objective [7], [5]. Seen the importance of such a process, systems of traditional air conditioning used in the habitat (refrigerated machine) are too expensive and cannot be put in work in the conditions of production. Other methods such as the statistical ventilation (roofing), the screens of shadiness or the cooling evaporative (moistening) can be adopted. Interactions between the internal and external variables and complexity of the phenomena (multivariable, nonlinear, no stationary) are such that it is often difficult to implement these methods.

Recently, much effort has been devoted to developing new control strategies of a greenhouse climate. In this respect, a large effort was devoted to develop adequate

greenhouse climate and crop models, for simulation, control and management purposes [6], [11]. The study and design of efficient greenhouse environmental controllers require having a priori knowledge of the greenhouse climate models [10]. These models must be related with the external nuances of the outside weather conditions (such as solar radiation, outside air temperature, wind velocity, etc.), and with the actuating actions performed (such as ventilation, cooling, heating, among others). The interdependence of the temperature and the humidity requires a control strategy which takes into account the relationship between these two parameters, thus the approach proposed in this work is oriented in the synthesis of intelligent climate decentralized controller based on the fuzzy logic.

Fuzzy set theory allows the use of linguistic concepts for representing quantitative values and can be employed to describe the greenhouse climate based on the system identification approach [2], [8]. Compared to traditional mathematical modelling, fuzzy modelling possesses some distinctive advantage, such as the mechanism of reasoning in human understandable terms, the capacity of taking linguistic information from human experts and combining it with numerical data and the ability of approximating complex nonlinear functions with simple models. Moreover, fuzzy system modelling is a powerful technique to describe complex dynamic systems [4], [5]. Based on the results of identification obtained in [1] we present, in this work, a fuzzy decentralized controller to control the greenhouse air temperature and humidity which is a complex system multivariable, nonlinear and non stationary. To reduce this complexity we propose to decompose the global system MIMO (Multi Input–Multi Output) on two subsystems MISO (Multi Input–Single Output).

The paper is organized as follows: in Section 2, we describe a greenhouse model. The synthesis of the fuzzy decentralized controller is designed in Section 3. In Section 4, simulation results are provided to demonstrate the effectiveness of the proposed method.



2. Formulation problem

The agriculture greenhouse is an area that permits to provide and maintain the creation of a favourable environment to plant to growth. The regulation of the greenhouse must take in consideration the evolution of the meteorological variables and the thermal state. We are in presence of MIMO system, non-linear and non-stationary in which intervene the energizing exchanges of the biologic functions assuring the development of the plants. Many works have been done on the development of the models of the greenhouse [11], [10], [3], [14] and [13] which are grouped on two categories: statistical and dynamics models.

The important number of variables (references, perturbations and commands) and the complexity of phenomena (biologic, weather, evolution of the plants ...) make that we have a multivariable system, non-linear and non-stationary [5], (figure 1.a). For these reasons, we thus preferred to apply a multimodal based on fuzzy logic and taken into account all the variables presented on figure 1.a.

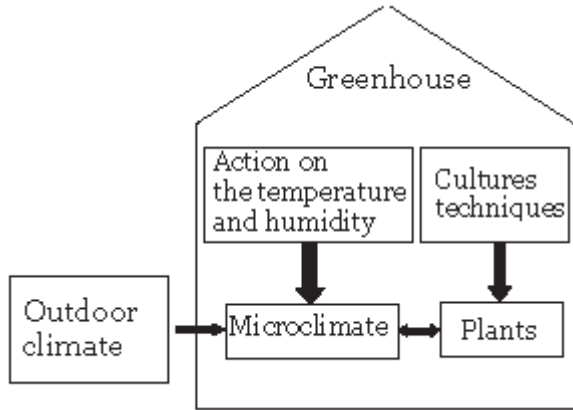


Figure 1.a. Block diagram of the greenhouse model

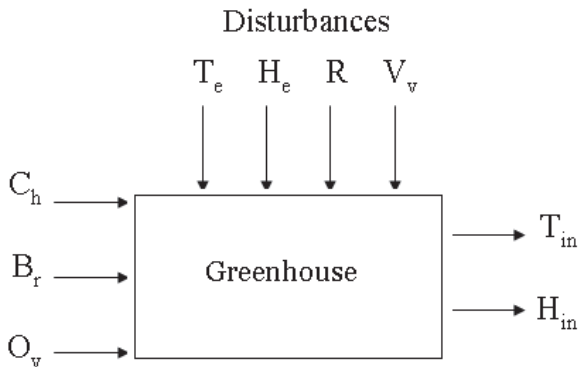


Figure 1.b. Input/Output diagram of greenhouse

where, T_i and H_i are respectively temperature and relative humidity of the internal air, the perturbation variables are T_e (external temperature), H_e (external humidity), R_g (solar radiation), V_v (wind velocity) and the input variable are C_h (heating), B_r (moistening) and O_v (roofing).

To simplify the complexity of the considered system greenhouse, we have proposed to decompose the MIMO (Multi Input–Multi Output) system into a MISO (Multi

Input–Single Output) system. By this decomposition, the identification and control are collected at level on each MISO subsystems; which avoid the computational load of the global approach. The nonlinearity, interactions between the loops and disturbances are taken into account by using the Takagi-Sugeno (TS) modeling. This technique can easily transform the nonlinearity problem to a linear one. The TS model is defined by the rules, which are linear conclusions of the systems outputs (internal temperature T_i and internal hygrometry H_i)

$$\begin{aligned} Ti(k+1) = & a_1 Ov(k) + a_2 Ch(k) + a_3 Br(k) + a_4 Te(k) \\ & + a_5 He(k) + a_6 Rg(k) + a_7 Vv(k) + a_8 Ti(k) + a_9 Hi(k) \end{aligned} \quad (1)$$

$$\begin{aligned} Hi(k+1) = & b_1 Ov(k) + b_2 Ch(k) + b_3 Br(k) + b_4 Te(k) \\ & + b_5 He(k) + b_6 Rg(k) + b_7 Vv(k) + b_8 Ti(k) + b_9 Hi(k) \end{aligned}$$

For the rule j , we obtain:

If $(Ov(k), Ch(k), \dots, Rd(k))$ is V_j then

$$\begin{aligned} Ti_j(k+1) = & a_{j1} Ov(k) + a_{j2} Ch(k) + a_{j3} Br(k) \\ & + a_{j4} Te(k) + a_{j5} He(k) + a_{j6} Rg(k) \\ & + a_{j7} Vv(k) + a_{j8} Ti(k) + a_{j9} Hi(k) \end{aligned} \quad (2)$$

If $(Ov(k), Ch(k), \dots, Rd(k))$ is W_j then

$$\begin{aligned} Hi_j(k+1) = & b_{j1} Ov(k) + b_{j2} Ch(k) + b_{j3} Br(k) \\ & + b_{j4} Te(k) + b_{j5} He(k) + b_{j6} Rg(k) \\ & + b_{j7} Vv(k) + b_{j8} Ti(k) + b_{j9} Hi(k) \end{aligned}$$

where

$\hat{\theta}_{1j} = [a_{j1} \ a_{j2} \ \dots \ a_{j9}]$ and $\hat{\theta}_{2j} = [b_{j1} \ b_{j2} \ \dots \ b_{j9}]$ are respectively model parameters for temperature and humidity for the rule j and $1 \leq j \leq M$ (M is the number of rules).

We define:

$$Z(k) = [Ov(k) \ Ch(k) \ Br(k) \ Te(k) \ He(k) \ Rg(k) \ Vv(k) \ Ti(k) \ Hi(k)] \quad (3)$$

and

$$Y_j(k) = \begin{bmatrix} Ti_j(k) \\ Hi_j(k) \end{bmatrix}, \quad \hat{\theta}_j = \begin{bmatrix} a_{j1} & a_{j2} & \dots & a_{j9} \\ b_{j1} & b_{j2} & \dots & b_{j9} \end{bmatrix} \quad (4)$$

$$Y_j(k) = \hat{\theta}_j^T(k) Z(k)$$

The vectors V_j and W_j represent a multi dimension centers of membership functions [1].

3. Fuzzy decentralized control

The structure of the MIMO fuzzy controller has three variables in inputs and two variables in outputs. The construction of fuzzy controller is a complex task, because many parameters are required for its design. To reduce the complexity, we have decomposed the global system on two subsystems. The first is defined with two inputs and one output, the second is defined with one input and one output (figure.2.a). The decomposition of



the system into two subsystems is based on the fact that the temperature is much influenced by the heating and the action of roofing, the humidity is influenced by the moistening.

For the first subsystem, we define a fuzzy controller, named fuzzy controller.1 (FC1) with four inputs and two outputs, for the second subsystem a fuzzy controller.2 (FC2) with four inputs and one output (figure.2.b).

Fuzzy controller in closed loop for the greenhouse is illustrated in figure.2.c

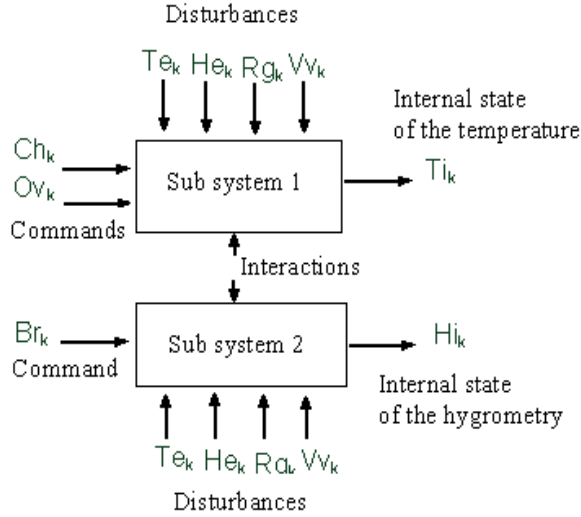


Figure 2.a. Inputs and Outputs selected

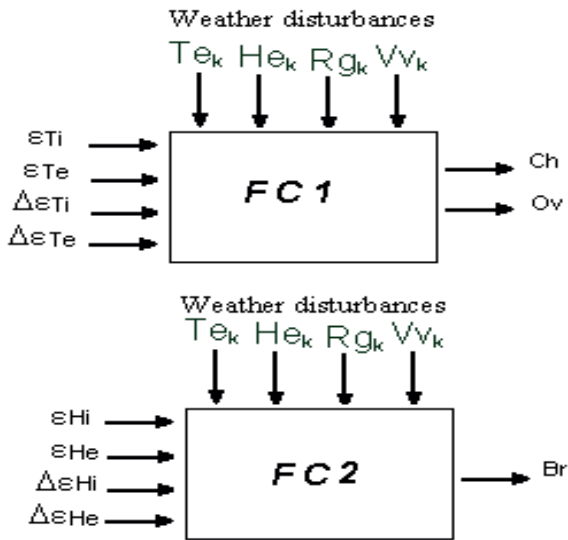


Figure 2.b. Fuzzy controllers (FC1 and FC2)

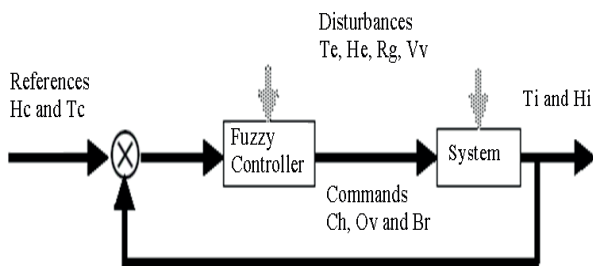


Figure 2.c. Fuzzy controller in closed loop for a Greenhouse

We use the temperature and humidity variation compared to their references εT_i and εH_i respectively and their variations.

$$\varepsilon T_i = T_{ic} - T_i, \Delta \varepsilon T_i(k) = \varepsilon T_i(k) - \varepsilon T_i(k-1),$$

$$\varepsilon T_e = T_e - T_i, \Delta \varepsilon T_e(k) = \varepsilon T_e(k) - \varepsilon T_e(k-1)$$

$$\varepsilon H_i = H_{ic} - H_i, \Delta \varepsilon H_i(k) = \varepsilon H_i(k) - \varepsilon H_i(k-1),$$

$$\varepsilon H_e = H_e - H_i, \Delta \varepsilon H_e(k) = \varepsilon H_e(k) - \varepsilon H_e(k-1).$$

All the inputs of the both considered controller FC1 and FC2 are three membership functions negative (n), null (z) and positive (p) (figure 3):

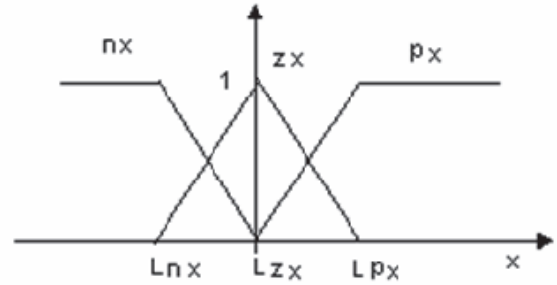


Figure 3. Representation of a linguistic variable

with $x \in \{\varepsilon T_i, \varepsilon T_e, \Delta \varepsilon T_i, \Delta \varepsilon T_e, \varepsilon H_i, \varepsilon H_e, \Delta \varepsilon H_i, \Delta \varepsilon H_e\}$, and $Ln x, Lz x$ et $Lp x$ represent the centre of the fuzzy subsets A_x^1, A_x^2 et A_x^3 .

Fuzzy controller 1:

R_1^1 : if εT_i is $A_{1\varepsilon T_i}^k$ and $\Delta \varepsilon T_i$ is $A_{1\Delta \varepsilon T_i}^k$ and εT_e is $A_{1\varepsilon T_e}^k$ and $\Delta \varepsilon T_e$ is $A_{1\Delta \varepsilon T_e}^k$ then Ch is C^l and Ov is O^l (5)

with

$A_{lx}^k \in \{n, z, p\} (k = 1, 2, 3), C^l \in \{No Heating, Heating\},$

$O^l \in \{open, no action, closed\}$ and l index of rule.

Fuzzy controller 2:

R_1^1 : if εH_i is $A_{1\varepsilon H_i}^k$ and $\Delta \varepsilon H_i$ is $A_{1\Delta \varepsilon H_i}^k$ and εH_e is $A_{1\varepsilon H_e}^k$ and $\Delta \varepsilon H_e$ is $A_{1\Delta \varepsilon H_e}^k$ then Br is B^l (6)

with $B^L \in \{No Moisterning, Moisterning\}$

The goal searched of this work is the regulation of the temperature and the humidity inside the greenhouse. In the simulation we choose the centre of the fuzzy subsets in the order as given in figure 3: $L_p = (5, 8, 3, 5, 10, 10, 6, 8),$

$L_z = \text{zeros}(1, 8)$ and $L_n = -L_p$

4. Simulation results

In order to validate the proposed approach in simulation of day, we have used the results obtained by the classical command (on-off) in the presence of the disturbances. The file which containing the results of state the day is composed of nine colons $Ov, Ch, Br, Te, He, Rg, Vv, Ti, Hi$ Using the classical command (on-off), the evolutions of the internal, external temperature and hygrometry are respectively on figures 4 and 5.



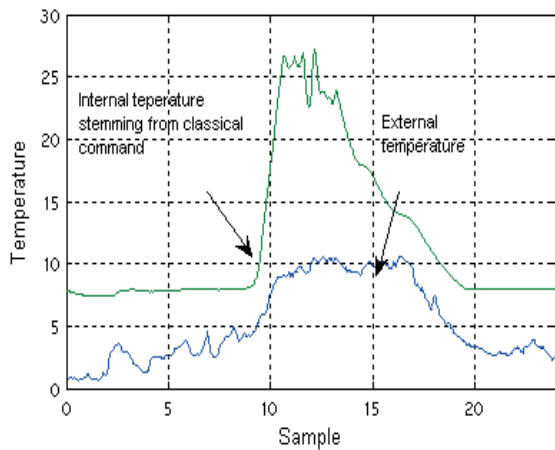


Figure 4. Temperature curve for the command (on-off)

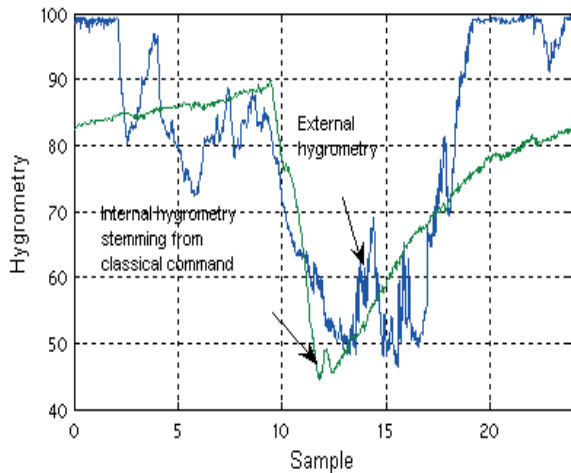


Figure 5. Hygrometry curve for the command (on-off)

To prove the performance of the proposed approach, we have chosen different forms of references.

First case

We take the internal temperature and hygrometry stemming from the classical command (on-off) as a references signal. The figures 6 and 7 show that the internal temperature and humidity stemming from the proposed fuzzy decentralized controller react correctly with the variation of the reference.

Second case

The reference signal of temperature and hygrometry are fixed ($T_{ref} = 20^{\circ}\text{C}$, $H_{ref} = 80\%$) for all day. From the figures 8 and 9 we can see that a good tracking is obtained, which prove the efficiency of the proposed approach.

On the figures 6, 8 and 7, 9 respectively, of the samples 0h to 12h and 17h to 24h, we note that the internal temperature and hygrometry are closed to the references signals, but at 12h to 17h the figures show that there exist the oscillations. In the general, the evolution of internal temperature and hygrometry are the same at the evolution of external temperature and hygrometry with a simple amplification.

Remark: All the oscillations observed on period between 12h to 17h are natural, because this period is a critical one on the day.

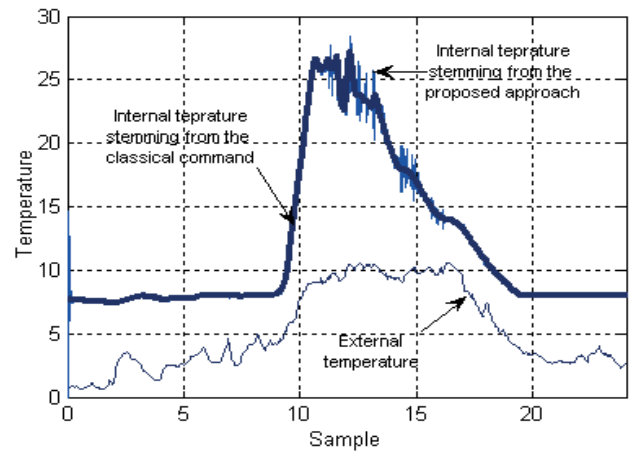


Figure 6. Temperature curve for the fuzzy decentralized controller 1

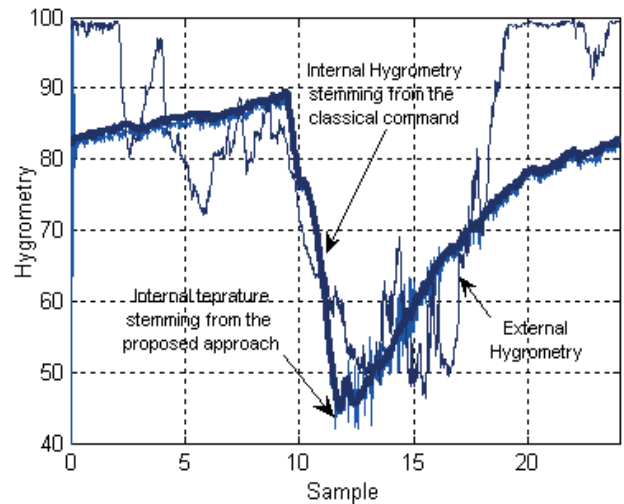
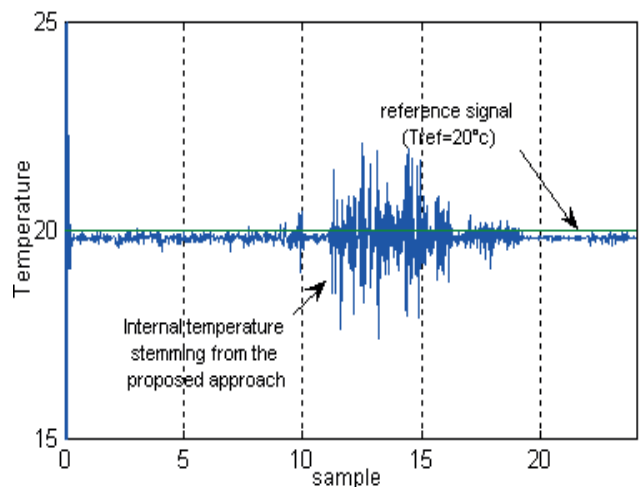


Figure 7. Hygrometry curve for the fuzzy decentralized controller 2

Figure 8. Temperature curve for the fuzzy decentralized controller 1 ($T_{ref}=20^{\circ}\text{C}$).

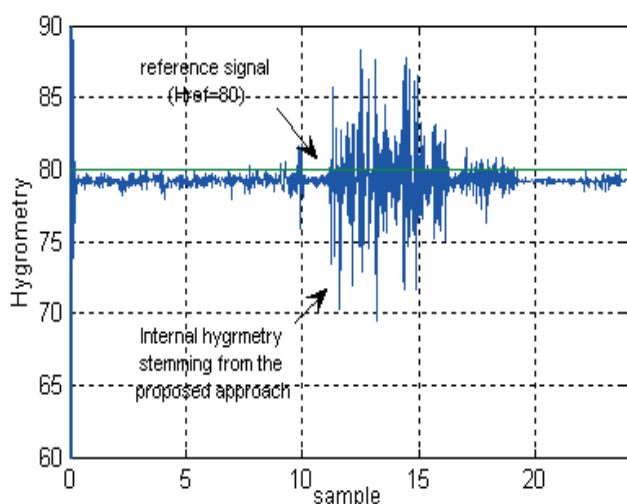


Figure 9. Hygrometry curve for the fuzzy decentralized controller 1($H_{ref}=80\%$)

The roofing is active when the temperature is high, this corresponds to the activation of the roofing command stemming from the classical command (on off).

We note that the moistening command is not active, the same case is recorded for the moistening command stemming from the on off command. It was also noted that the heating command has not been activated at the same time as the classical command (on off), but it was active in areas that are characterized by fluctuations

5. Conclusion

To reduce the complexity of the greenhouse, which is multivariable, non-linear and non stationary in nature, we have proposed to decompose the MIMO system into MISO subsystems. By this decomposition, the MISO subsystems are represented by compact Takagi-Sugeno (TS) model and convert a nonlinear problem into linear one. The results obtained, show that the proposed fuzzy decentralized controller can be applied to control the greenhouse climate.

6. References

- [1] A. Errahmani, M. Benyakhlef and I. Boumhidi, Greenhouse Model Identification based on Fuzzy Clustering Approach, ICGST-ACSE Journal, ISSN 1687-4811, Volume 9, Issue II: 23-27, October 2009.
- [2] M. Souissi, M. Chaabane and A. Toumi; Greenhouse climate discrete control with guaranteed H_∞ performance, International Journal of Computational Cognition, Volume 3: 27-33, 2005.
- [3] P. M. Ferreira, A.E. Ruano, Soft-computing methods in greenhouse environmental and crop modelling, EFITA/WCCA Joint Congress on in Agriculture, 280-287, 2005.
- [4] F. Lafont, J. F. Balmat, Fuzzy logic to the identification and the command of the multidimensional systems, International Journal of Computational Cognition, Volume 2: 21-47, 2004.
- [5] I. Laribi Maatoug, R.Mhiri, An Explicit Solution for the Optimal Control of Greenhouse Temperature relying on Embedded System, ICGST-ACSE, Volume 8, Issue I, ISSN: 1687-4811, 2004
- [6] G. D. Pasgianos, K.G. Arvanitis, P. Polycarpou and N. Sigrimis, A non-linear feedback technique for greenhouse environmental control, Computers and Electronics in Agriculture. Volume 40: 153-177, 2003.
- [7] F. Lafont, J. F. Balmat, Optimized fuzzy control of a greenhouse, Fuzzy Sets and Systems, 128: 47-59, 2002.
- [8] J.C. Roy, T. Boulard, C. Kittas and S. Wang, Convective and ventilation transfers in greenhouse, part 1: the greenhouse considered as perfectly stirred tank, Biosystems Engineering, 83(1): 1-20, 2002.
- [9] N. Sigrimis, K.G. Arvanitis, K.P. Ferentinis and A. Anatsiou, An intelligent no interacting technique for climate control of greenhouse, IFAC, 15th Triennial World Congress, Barcelona Spain, 2002.
- [10] C. Tavares, A. Goncalves, P. Castro, D. Loureiro, A. Joyce, Modelling an agriculture production greenhouse, Renewable Energy, 22: 15-20, 2001.
- [11] T. Boulard, S. Wang, Greenhouse crop transpiration simulation from external climate conditions, Agriculture and Forest Meteorology, 100(1): 25-34, 2000.
- [12] J. Boaventura, C. Couto and A.E. Ruano, Real time parameter estimation of dynamic temperature models for greenhouse environmental control, Cont. Eng and Practice, Volume 5 N° 10: 1473-1481, 1997.
- [13] C. Viard Gaudin, Simulation in greenhouse climate control, Acta Horticulture 174: 461-467, 1985
- [14] T. Takakura, K.A. Jordan, L.L. Boyd, Dynamic simulation of plant growth and environment in the greenhouse, Trans. ASAE 14: 964, 1971.



Biographies



Ahmed Errahmani, received his Master's degree in 2004 from the University Sidi Mohamed Ben Abdellah, Faculty of Sciences, Fèz Morocco. He is pursuing his Ph. D. degree. His research areas include fuzzy control of non-linear systems.



Majid Benyakhlef, received the graduated from the University of Mohamed V, Faculty of science Rabat, He received a Ph. D. degree in 2006 from the University Sidi Mohamed Ben Abdellah Faculty of sciences, Fez. He has been a Professor assistant of Informatique

and Automatic control at the Faculty Polydisciplinaire of Taza. Currently, his research interests include decentralized robust control, fuzzy control and adaptive control of large scale systems.



Ismail Boumhidi is a Professor of electronics at the Faculty of Sciences, Fez Morocco. He received from the University Sidi Mohamed ben Abdellah Faculty of sciences his "Doctorat de 3^{ième} cycle" degree in 1994 and "Doctorat d'Etat" degree in 1999.

His research areas include adaptive robust control, multivariable nonlinear systems, and fuzzy logic control with applications.





Improvement of Voltage stability and Critical Clearing Time for Multi-machine Power Systems Using Static VAR Compensator

Ashraf Mohamed Hemeida, Ph.D. Associate Professor

Electrical Engineering Department, High Institute of Energy

South Valley University, Aswan – EGYPT

Currently: Chairman of Computer Science Dept., Arrass Faculty of Science & Arts, Qassim University, K.S.A

ahemeida@yahoo.com

Abstract

The present paper studies the effect of equipping static VAR compensator, SVC in multi-machine power system to improve the voltage stability and critical clearing time CCT. of multimachine power system. Three static VAR compensators, SVCs are connected with certain power system buses to stabilize the system voltage and improve the overall power system stability subjected to different disturbances for a wide range of operating conditions. Also, the SVCs improve the power system critical clearing time to a significant values in case of unrepeatd three phase short circuit fault at all system buses for different operating conditions. The results indicate the importance of installing SVCs to grid power system due to their effect not only on stabilizing the system voltages but also increasing the power system critical clearing time. The critical clearing time is obtained by increasing the fault time interval until the system loses its stability. Increasing the CCT can help in the reliability of the protection system and reduce the protection system rating and its cost. The studied 3-machine nine- bus power system is modeled and simulated using MATLAB software package.

Keywords

Multi-machine power system - Voltage stability improvement – Static VAR Compensator - Critical clearing time.

Nomenclature

$\delta_i(t)$ Generator rotor angle
 ω_i Relative speed of the i^{th} gen. in p.u.
 ω_s Synchronous speed in p.u.
 T_{mi} Mech. input torque, in p.u..
 T_{ei} Elec. torque, in p.u. .
 E_{qi} Transient EMF in quad. axis, in p.u..
 I_{di} Direct axis current, in p.u
 I_{qi} Quad. axis current, in p.u..
 D_i Per unit damping constant.
 H_i Inertia constant in second.
 T_{doi} Direct axis transient s. c. time const. in sec.

T_{qoi} Quad. axis transient s. c. time const. in sec.

x_{doi} Direct axis reactance in p.u.

x_{doi} Quad. axis reactance in p.u.

x_{doi} Direct axis transient reactance in p.u.

x_{qoi} Quad. axis transient reactance in p.u.

E_{fi} Field voltage in per unit.

K_{Ai} Gain of the excitation amp.

B_L : Inductive susceptnce of the SVC.

B_C : Capacitive susceptnce of the SVC

1. Introduction

Flexible Alternating Current Transmission System (FACTS) devices are used extensively to increase the amount of power transferred of the transmission systems and increase the power system stabilization[1-4]. Static VAR compensators (SVCs) are used in power systems in both transmissions and distribution systems. The main objective of installing SVCs in electric power system is to provide rapid control of voltages at weak points in electric power systems. SVCs is used also to provide system stabilization in case of insufficient damped inter-area oscillations and improve the power system power quality[5-6]. SVCs should be controlled in order to provide rapid and continuous reactive power during steady state and dynamic operating conditions. The application of SVCs in Extra High Voltage, EHV network to provide a dynamic reactive power compensation to keep the bus voltages within the permissible values under varying load conditions, and improve voltage stability. The location and size of SVCs have been discussed in details in both transient and steady state[7]. The application of multiple compensation have been considered by the utilities to meet the performance objectives. These objectives are considered based on evaluate different goals, such as improving power system network voltage profile, reducing the power system losses, increasing the power transmissions, damping the power system oscillations, and improving the overall power system stability[8-13]. Recently, there are different control techniques have been applied to provide (SVCs) rapid response such as self tuning, fuzzy logic, neural network, neurofuzzy[14-17].



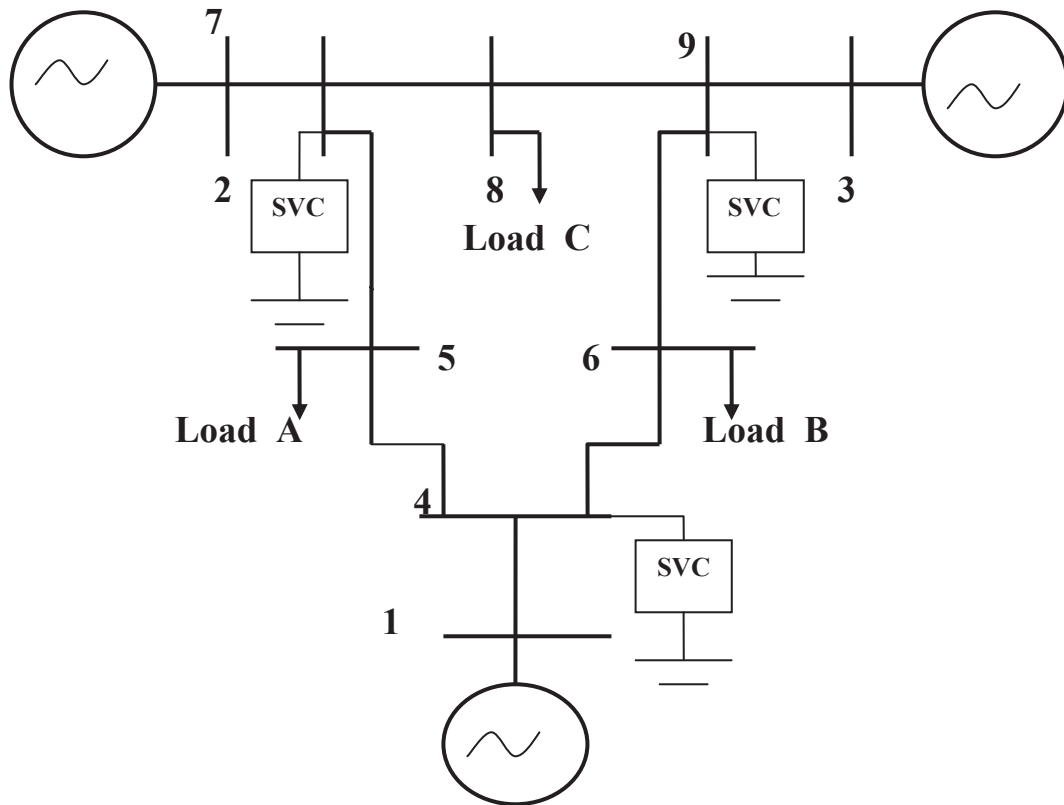


Figure 1 IEEE WSCC 3 Machine 9-bus Power System

The stability analysis of power systems may consider the determination of the system critical clearing time, CCT for a given fault in order to find the maximum value of CCT for which the system is still stable. If the fault is cleared within this time the system will remain stable. However if the fault cleared after this time the power system will lose its stability. The calculation of CCT is very important from the protection point of view. This will aid to determine the characteristics of protection system required to the power systems. There are several conventional methods to compute the CCT, such as numerical integration and Lyapunov-type stability criteria[18]. Recently the neural network approach have been used extensively to determine the critical clearing time of power systems[19-23].

This paper presents the effect of installing static VAR compensators (SVCs) to multi-machine power systems. The results obtained investigate that installing SVCs stabilize the power systems voltages and damp the oscillations in case of disturbance very fast. The studied multi-machine power system have been simulated and the critical clearing time is obtained with and without installing (SVCs). The result indicates that with installing (SVCs) the critical clearing time, CCT have been increased. The studied system is IEEE WSCC 3 Machines 9-bus Power System.

2. Modeling of the Presented Power System

The multimachine power system under study with three SVCs connected at certain buses is shown in Figure1. Different models have been used for stability studies. 7th order model for the time simulation of studied power system is implemented. Each synchronous generator is equipped with IEEE-Type I Exciter model[24].

$$\frac{d\delta_i}{dt} = \omega_i - \omega_s \quad (1)$$

$$M_i \frac{d\omega_i}{dt} = T_{mi} - (E_{qi}^{\lambda} - X_{di}^{\lambda} I_{di}) I_{qi} - (E_{di}^{\lambda} + X_{qi}^{\lambda} I_{qi}) I_{di} - D_i (\omega_i - \omega_s) \quad (2)$$

$$T_{doi}^{\lambda} \frac{dE_{qi}^{\lambda}}{dt} = -E_{qi}^{\lambda} - (X_{di}^{\lambda} - X_{di}^{\lambda}) I_{di} + E_{fdi} \quad (3)$$

$$T_{qoi}^{\lambda} \frac{dE_{di}^{\lambda}}{dt} = -E_{di}^{\lambda} + (X_{qi}^{\lambda} - X_{qi}^{\lambda}) I_{qi} \quad (4)$$

$$T_{Ei} \frac{dE_{fdi}}{dt} = -[K_{Ei} + S_{Ei}(E_{fdi})] E_{fdi} + V_{Ri} \quad (5)$$

$$T_{Ai} \frac{dV_{Ri}}{dt} = -V_{Ri} + K_{Ai} R_{fi} - \frac{K_{Ai} K_{Ri}}{T_{Ri}} E_{fdi} + K_{Ai} (V_{refi} - V_{ti}) \quad (6)$$

$$T_{Fi} \frac{dR_{Fi}}{dt} = -R_{Fi} + (K_{Fi}/T_{Fi}) E_{fdi} \quad (7)$$



The algebraic equations are:

$$V_{ii} = (V_{di}^2 + V_{qi}^2)^{1/2} \quad (8)$$

$$V_{di} = E_{di} - R_e I_{di} + X_e I_{qi} \quad (9)$$

$$V_{qi} = E_{qi} - R_e I_{qi} - X_e I_{di} \quad (10)$$

$$I = YV \quad (11)$$

$$I_i = (i_d + j i_q) e^{j(\delta_i - \pi/2)} \quad (12)$$

$$V_i = (V_d + j V_q) e^{j(\delta_i - \pi/2)} \quad (13)$$

$$Y_{ii} = y_{ii} e^{j\beta_{ii}} \quad (14)$$

For the study of the system stability, the previous equations are solved by **Matlab** software.

3. Static VAR Compensator Model

The SVC model used in this study is fixed capacitor, thyristor controlled reactor(FC-TCR) type as shown in figure 2. By changing the thyristor firing angle (alpha), the reactor current can be controlled according to the following equations [14] :

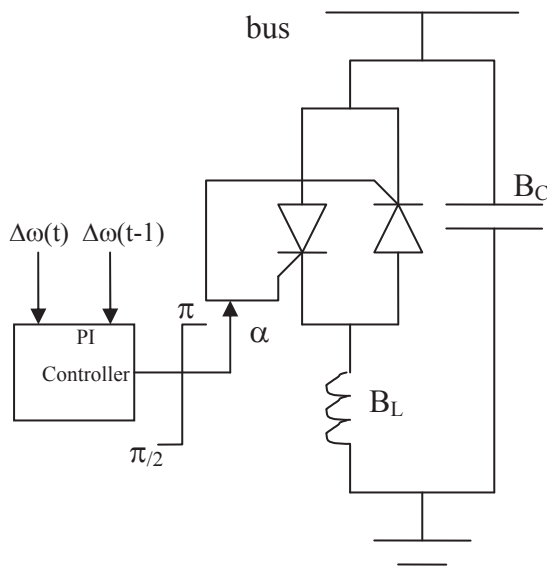


Figure 2 Schematic Diagram of FC-TCR SVC type

$$I_L(\alpha) = \frac{V(2\pi - 2\alpha + \sin 2\alpha)}{\pi \omega L} \quad (15)$$

$$\text{where } \frac{\pi}{2} \leq \alpha \leq \pi$$

$$I_L(\sigma) = \frac{\sigma - \sin \sigma}{\pi \omega L} V \quad (16)$$

The reactor susceptance is given as :

$$B_L(\sigma) = \frac{I_L(\sigma)}{V} \quad (17)$$

From equations (16),(17) the susceptance can be obtained as :

$$B_L(\sigma) = \frac{\sigma - \sin \sigma}{\pi \omega L} \quad (18)$$

However the equivalent SVC susceptance is given by the summation of the fixed capacitor susceptance and the thyristor controlled reactor susceptance as follows:

$$B_{SVC} = B_C - B_L(\sigma) \quad (19)$$

The conduction angle σ and the firing angle α are related by the following equation:

$$\sigma = 2(\pi - \alpha)$$

The SVC model is added to the system equations and solved using matlab software to obtain the critical clearing time CCT of the studied power system and study the effect of installing SVC in voltage stability enhancement.

4. PI Controller

PI controller is used in this study due to it's applicable device. The block diagram of the SVC PI controller is shown in figure 3. The equation describe the PI controller can be expressed as:

$$\alpha(t) = \Delta T [\Delta \omega(t) K_I + K_P (\Delta \omega(t) - \Delta \omega(t-1))] + \alpha(t-1) \quad (20)$$

Where: $\pi/2 \leq \alpha(t) \leq \pi$

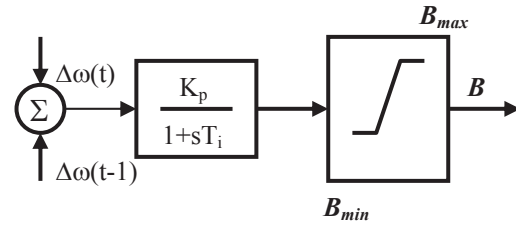


Figure 3 Block Diagram of SVC PI controller

5. Results and Discussions

The parameter data of studied power system are given in the appendices . The load flow study is performed firstly to determine the critical clearing time of the studied power system. Different load conditions are applied in order to evaluate the effect of installing SVC on the power system critical clearing time and the bus voltages after applying mechanical input power disturbance. Table 1 gives the steady state load flow results of the studied power at different operating conditions. Figure 7 shows the flowchart of computer solution to the studied system.

Table 1 : The buses voltages of the Load flow results of the studied system at different operating conditions.

Load % Bus #	25	50	75	100	125	150
1	1.040	1.040	1.040	1.040	1.040	1.040
2	1.025	1.025	1.025	1.025	1.025	1.025
3	1.025	1.025	1.025	1.025	1.025	1.025
4	1.057	1.048	1.037	1.026	1.013	0.998
5	1.059	1.040	1.019	0.996	0.969	0.939
6	1.064	1.049	1.032	1.013	0.992	0.968
7	1.050	1.043	1.035	1.026	1.014	1.001
8	1.053	1.042	1.030	1.016	1.000	0.981
9	1.051	1.046	1.039	1.032	1.024	1.014

5.1 Critical clearing time evaluation

In order to obtain the critical clearing time for the studied power system , the power system load is increased gradually and load flow study is executed for the stability study. The CCT can be obtained by increasing the time interval of the fault gradually till the studied system loses its stability. To study the powerful of the proposed SVC controller. three SVCs are connected at the buses number 4, 7, 9. of the studied power system as shown in



figure 1 and the fault interval time increases gradually up till the system loses its stability and then the CCT can be determined .

Table 2 to Table 10. shows the studied power system critical clearing time with and without installing static VAR compensator at different load level. It is very clear that the effect of installing SVC in increasing the CCT up to 200% in some cases very clear. This will aid to choose the suitable protection system.

Table [2]: Critical clearing time with and without the proposed SVC at different loading levels when the Fault occurs at bus # 1:

% of load level	CCT without SVC In m.sec.	CCT with SVC In m.sec
25	122	223
50	116	215
75	110	193
100	104	189
125	98	182
150	92	176

Table [3]: Critical clearing time with and without the proposed SVC at different loading levels when the Fault occurs at bus # 2:

% of load level	CCT without SVC In m.sec.	CCT with SVC In m.sec
25	133	249
50	126	242
75	119	233
100	108	216
125	101	208
150	95	187

Table [4]: Critical clearing time with and without the proposed SVC at different loading levels when the Fault occurs at bus # 3:

% of load level	CCT without SVC In m.sec.	CCT with SVC In m.sec
25	139	269
50	131	258
75	121	247
100	114	223
125	109	205
150	101	195

Table[5]: Critical clearing time with and without the proposed SVC at different loading levels when the Fault occurs at bus #4:

:% of load level	CCT without SVC In m.sec.	CCT with SVC In m.sec
25	434	845
50	401	823
75	369	673
100	256	494
125	109	217
150	91	163

Table [6]: Critical clearing time with and without the proposed SVC at different loading levels when the Fault occurs at bus # 5

% of load level	CCT without SVC In m.sec.	CCT with SVC In m.sec
25	161	307
50	126	231
75	105	186
100	91	147
125	82	123
150	73	97

Table [7]:Critical clearing time with and without the proposed SVC at different loading levels when the Fault occurs at bus #6:

% of load level	CCT without SVC In m.sec.	CCT with SVC In m.sec
25	134	253
50	127	238
75	122	227
100	109	221
125	103	213
150	98	202

Table [8]:Critical clearing time with and without the proposed SVC at different loading levels when the Fault occurs at bus # 7:

% of load level	CCT without SVC In m.sec.	CCT with SVC In m.sec
25	462	834
50	421	713
75	343	587
100	223	386
125	141	237
150	123	203

Table [9]:Critical clearing time with and without the proposed SVC at different loading levels when the Fault occurs at bus # 8:

% of load level	CCT without SVC In m.sec.	CCT with SVC In m.sec
25	503	969
50	482	933
75	463	902
100	441	857
125	234	441
150	141	265

Table [10]: Critical clearing time with and without the proposed SVC at different loading levels when the Fault occurs at bus # 9:

% of load level	CCT without SVC In m.sec.	CCT with SVC In m.sec
25	471	912
50	451	881
75	437	867
100	221	408
125	147	267
150	113	203

5.2 Voltage Stability Study

In order to indicate the effect of installing SVCs with each synchronous machine on enhancement of power system voltage stability, 0.02 p.u. input mechanical power disturbance is considered to each machine separately. Figure 4 depicts the power system bus voltage response with and without static VAR compensator when 2% input mechanical power disturbance is applied at the three machines each separately when the load is 50%. The effect of using SVC is very clear in damping the voltage oscillations very fast and improve the system performance. Figure 5 shows the machine bus voltages when the load is exceed to full load and 0.02 p.u. input mechanical power is considered. The performance with installing SVC is very clear in damping the bus voltages oscillations very fast. Figure 6 depicts bus voltages when the studied power system load became 125% with and without installing SVC. The effect of SVC in damping the machine bus voltages oscillation is clear.



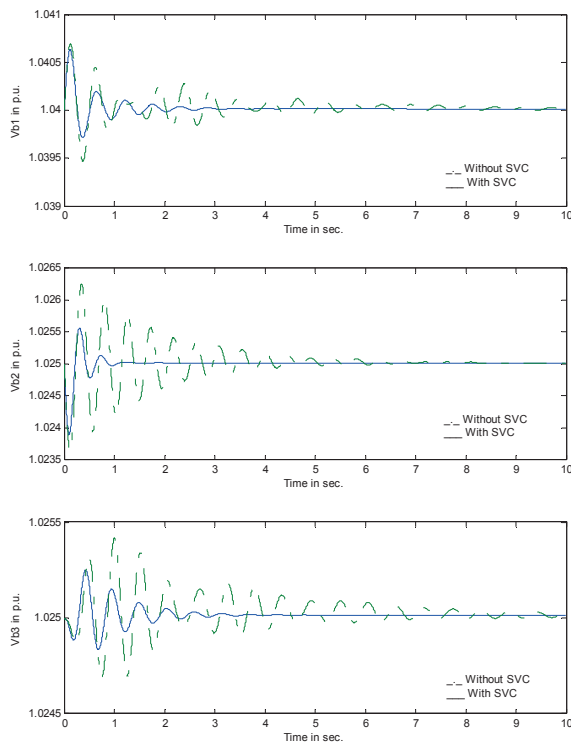


Figure 4 Studied System Voltage when 0.02 p.u. increased in input mechanical power (50% load)

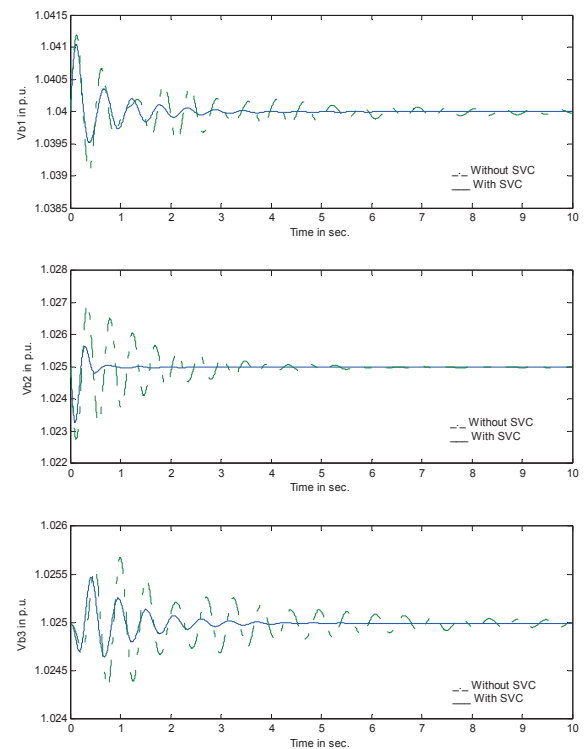


Figure 6 Studied System Voltage when 0.02 p.u. increase in input mechanical power (125% load)

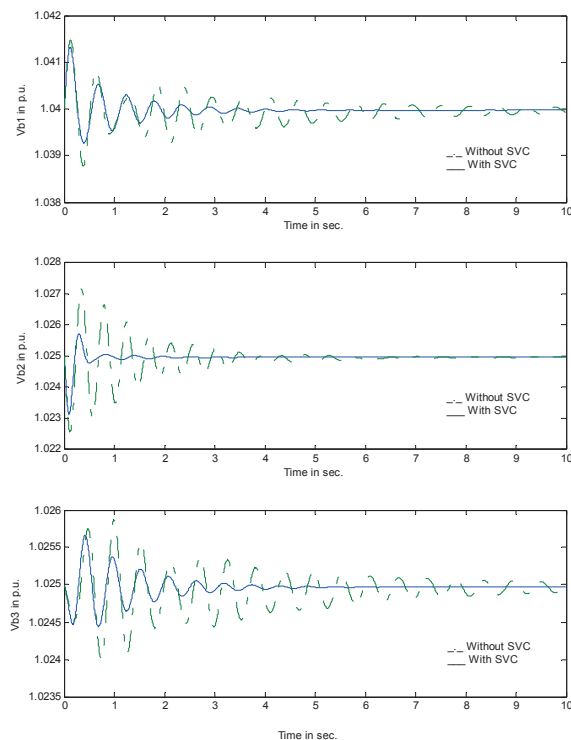


Figure 5 Studied System Voltage when 0.02 p.u. increase in input mechanical power (100% load)

6. Conclusions

This paper investigates the importance of equipping static VAR compensator with the power systems. Different load levels and different fault locations of the studied power system are suggested to study the effect of installing SVC in increasing the CCT, and stabilizing the studied power system voltages. The simulation results proved that connecting of SVC to the power system increases the power system critical clearing time with a specific values when a three phase short circuit fault is occurred. The installing SVCs to power systems can increase the CCT to very close to 200% in compared without installing SVCs. Also the power system voltages became more stable very fast when 0.02 p.u. of an input mechanical disturbance is considered to the synchronous machines at different operating conditions.

7. References

- [1] Hingorani N.G., "Flexible AC Transmission Systems", IEEE Spectrum, Vol. 30, No. 4, pp. 40-45, April 1993.
- [2] Hingorani N.G., Gyugyi, L., "Understanding FACTS, Concepts and Technology of Flexible AC Transmission Systems", IEEE Press, 2000.
- [3] Hammons T.J., Lim S.K., "Flexible AC Transmission System (FACTS)", Electric Machines and Power Systems Vol.25, pp. 73-85, 1997.



- [4] S.V Ravi Kumar and S. Siva Nagaraju, "Transient stability improvement using UPFC and SVC", ARPN Journal of Engineering and Applied Sciences, VOL. 2, NO. 3, pp. 38-45, June, 2007.
- [5] Gotham D. J., Heydt G.T., "Power Flow Control and Power Flow Studies for Systems with FACTS Devices", IEEE Trans on Power Systems Vol.13, No. 1, pp. 60-65, February 1998.
- [6] Arabi S., Kundur P., "A Versatile FACTS Device Model for Power Flow and Stability Simulations", IEEE Trans on Power Systems, Vol. 11, No. 4, pp. 1944-1950, November 1996.
- [7] IEEE Special Stability Controls Working Group, "Static VAR Compensator Models for Power Flow and Dynamic Performance Simulations", IEEE Trans. Power Systems, Vol. 9 (1), pp. 229-240, 1994.
- [8] F.R. Quintela, J.M.G. Arévalo, R.C. Redondo, "Power analysis of static VAR compensators", International Journal of Electrical Power & Energy Systems, Volume 30, Issues 6-7, July- pp. 376-382, September 2008.
- [9] M. A. Al-Biati, M. A. El-Kady, A. A. Al-Ohaly, "Dynamic stability improvement via coordination of static var compensator and power system stabilizer control actions", Electric Power Systems Research, Volume 58, Issue 1, pp. 37-44, May 2001.
- [10] H. Brahmi, R. Dhifaoui, O. Hasnaoui, "A Voltage control scheme to enhance power systems voltage level" ACSE Journal, Vol. (5), Issue (III), pp. 9-15, Sept. 2005
- [11] San-Yi Lee, Chi-Jui Wu, Wei-Nan Chang, "A compact control algorithm for reactive power compensation and load balancing with static Var compensator", Electric Power Systems Research, Volume 58, Issue 2, pp. 63-70, June 2001.
- [12] M.R. Qader, "Optimal location of advanced static VAR compensator (ASVC) applied to non-linear load model" Energy, Volume 31, Issue 12, pp. 1761-1768, September 2006.
- [13] Jimmie J. Cathey, Wilda E. Moore, "Improvement of generator output and stability margin by use of a dedicated static VAR compensator", Electric Power Systems Research, Vol. 63, Issue 2, pp. 119-125, 2002.
- [14] Qun Gu, Anupama Pandey, Shelli K. Starrett, "Fuzzy logic control schemes for static VAR compensator to control system damping using global signal", Electric Power Systems Research, Volume 67, Issue 2, pp. 115-122, November 2003.
- [15] J. Lu, M. H. Nehrir, D. A. Pierre, "A fuzzy logic-based adaptive damping controller for static VAR compensator", Electric Power Systems Research, Volume 68, Issue 2, pp. 113-118, February 2003.
- [16] A.H.M.A.Rahim, M. Baber Abbas, "Self tuning adaptive pole-shift STATCOM Control for single and multi machine power systems" ICGST-ACSE Journal, Vol. 7, Issue 2, pp. 55-62, Nov. 2007.
- [17] H. Rastegar, M. Abedi, M. B. Menhaj, S. H. Fathi, "Fuzzy logic based static VAR compensators for enhancing the performance of synchronous and asynchronous motor loads" Electric Power Systems Research, Volume 50, Issue 3, pp. 191-204, June 1999.
- [18] Kundur, P., "Power System Stability and Control", McGraw-Hill, 1994.
- [19] Krishna, D.R.; Murthy, K.; Rao, G.G, "Application of Artificial Neural Networks in Determining Critical Clearing Time in Transient Stability Studies" IEEE Power India Int. Conference on Power System Technology POWERCON 2008, pp.1 – 6, 12-15 Oct. 2008
- [20] Jiriwibhakorn, S.; Pothisarn, C, "Application of nearest neighbor algorithm for critical clearing time (CCT) approximation. "IEEE/PES Transmission and Distribution Conference and Exhibition Asia Pacific, Vol. 3, 6-10, pp. 1530 – 1535, Oct. 2002.
- [21] Jiriwibhakorn, S.; Coonick, A.H, "Fast critical clearing time estimation of a large power system using neural networks and Sobol sequences", IEEE Power Engineering Society Summer Meeting, Volume 1, 16-20 pp. 522 – 527. July 2000
- [22] Wuxing Liang; Littler, T, "Calculation of Critical Clearing Time of Embedded Generation for Relay Setting Based on Optimization Method" IET 9th Int. Conference on Developments in Power System Protection, pp.246 – 251, 17-20 March 2008
- [23] Kunsong Huang; Dinming Lam; Hansen Yee, "Neural-net based critical clearing time prediction in power system transient stability analysis" 2nd International Conference on Advances in Power System Control, Operation and Management, APSCOM-93., 7-10 pp. 679 – 683, Dec 1993.
- [24] P. W. Saur and M. A. Pai, "Power System Dynamics and Stability" Book, Prentice Hall, Upper Saddle River, New Jersey 07458, 1998.

Appendix

The 3 machine nine bus power system line data

Line	SB	EB	Line	Y_{sh}		Z_s	
				g	jb	r	x
1	1	4	1	0.00	0.000	0.000	0.057
2	4	5	1	0.00	0.088	0.010	0.085
3	4	6	1	0.00	0.092	0.017	0.092
4	5	7	1	0.00	0.153	0.032	0.161
5	6	9	1	0.00	0.179	0.039	0.170
6	9	3	1	0.00	0.000	0.000	0.058
7	7	2	1	0.00	0.000	0.000	0.062
8	9	8	1	0.00	0.104	0.011	0.100
9	8	7	1	0.00.	0.074.	0.008.	0.072.

Three machines data:

	Mach.1	Mach.2	Mach.3
H	23.64	6.4	3.01
x_d (p.u)	0.1460	0.8958	1.3125
x_d' (p.u)	0.0608	0.1198	0.1813
x_q (p.u)	0.0969	0.8645	1.2578
x_q' (p.u.)	0.0969	0.1969	0.2500
T_{d0} sec.	8.960	6.00	5.89
T_q sec.	0.310	0.535	0.600



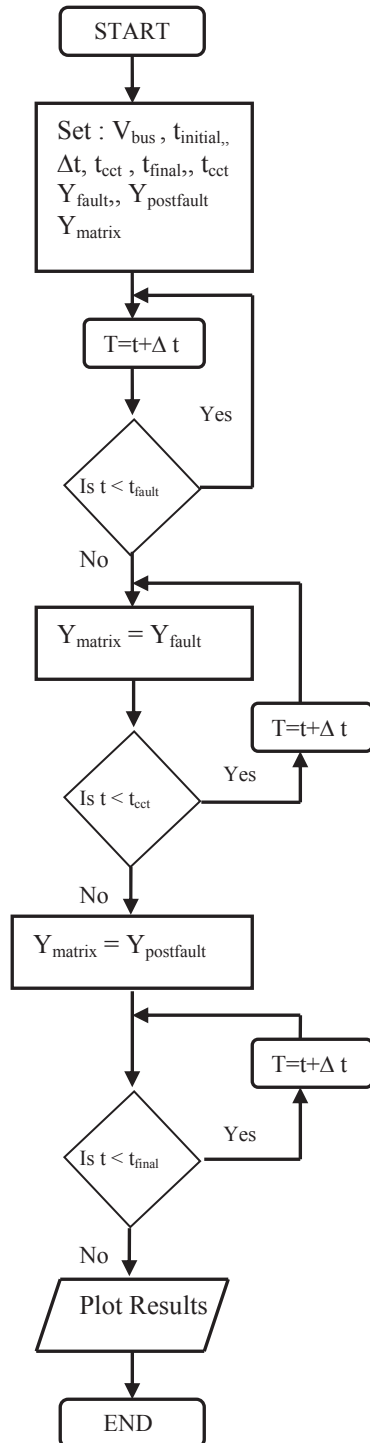


Figure 7 Flowchart of solution the studied system

Exciter data:

	K_A	$T_A(\text{sec.})$	K_E	$T_E(\text{sec.})$	K_F	$T_F(\text{sec.})$
Excit. 1	20	0.2	1.0	0.314	0.63	0.35
Excit. 2	20	0.2	1.0	0.314	0.63	0.35
Excit. 3	20	0.2	1.0	0.314	0.63	0.35

Power System Loads, in KVA:

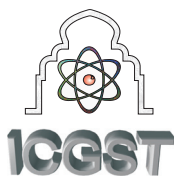
Load A = $125 + j 40$, Load B = $90 + j 30$,Load C = $100 + j 30$.**Biography**

Ashraf Mohamed Hemeida, was born in Elmenia, Egypt, on October, 21, 1968. He obtained his B.Sc., and M.Sc. in Electrical Power Engineering From faculty of Engineering, Elminia University, Elmenia, Egypt in 1992 and 1996 respectively. In Nov. 1992, He engaged Higher Institute of Energy,

Aswan as Teaching Assistant. From 1998 to 1999 He was a full time Ph.D. student with Electrical and Computer Engineering Department, University of New Brunswick, Canada. In Sept., 2000 He obtained his Ph.D. From Electrical Engineering Department, Faculty of Engineering, Assiut University, Assiut Egypt. From Oct. 2000 till August 2005 He was Assistant Professor at Electrical Engineering Department, Higher Institute of Energy, South Valley University, Aswan, Egypt. In Nov. 2005 He obtained Associate Professor rank. From Sept. 2006 till now he is the chairman of Computer Science Department, Arrass Faculty of Science and Arts, Qassim University, Kingdom of Saudi Arabia. His research interest power systems operational and control, artificial intelligence application in power systems, FACTS applications, and voltage stability.







Magnetic Analysis and Comparison of Switched Reluctance Motor with Different Stator Pole Shapes Using a 3D Finite Element Method

M. Sundaram, P. Navaneethan and M. Vasanthakumar

Department of Electrical and Electronics Engineering,

PSG College of Technology, Peelamedu, Coimbatore-641004.

msm@eee.psgtech.ac.in, pnn@eee.psgtech.ac.in, mvk@eee.psgtech.ac.in

www.psgtech.edu

Abstract

Optimum design of Switched Reluctance Motor (SRM) requires knowledge of its parameters, such as inductance, flux linkage and torque. In this paper, the model of SRM with two different stator pole shapes have been developed and analyzed with ANSYS (Analysis System) Workbench. The variation of inductance, flux density and directional force with respect to rotor position for both the models have been gathered, which are the fundamental characteristics of SRM and have significant influences on motor performance. It is observed that the proposed parallel slot type stator pole (model 2) gives the improved flux density and directional force/ Torque.

Keyword: *Switched Reluctance Motor, ANSYS, Flux linkage, Directional Force/Torque.*

1. Introduction

The theory of motor with variable reluctance has been started to be used since 1980's for the variable or adjusted speed application and the use of these motors started to be very popular in engineering applications. The advantages brought by the cheap and powerful switching elements enabled the re-discovery of this motor [1].

Many advanced manufacturing processes require smooth, high precision and/or high speed robotic manipulation in 3D space. Electrical Motors, as energy conversion devices, are widely used in industrial applications. The simulation and experimental investigations of the electromagnetic field distribution are one of critical topic for developing electromagnetic products [2]. Due to exclusive features of the SRM such as lack of any coil or permanent magnet on the rotor, simple structure and high reliability, this makes it a suitable candidate for operation in hard or sensitive conditions. Although the FEM was a time-consuming and difficult method in the past, with contemporary high speed computers with large memory, the method can be used properly in analysis of electric machines. In addition, various commercial finite-element packages ANSYS Workbench have been so far developed for this purpose [3].

In this paper, Switched Reluctance motor with two different pole configurations were taken for magnetic analysis. Section (2) describes about the parametric modeling of motors. Finite element method and assumptions made for the analysis were described in Section (3). Finally, a comparison of the two structures and conclusions are presented in Section (4) and (5) respectively.

2. The Parametric Simulation Model

The ANSYS Workbench platform is a powerful multi-domain simulation environment. Multiphysics simulation from ANSYS provides powerful simulation tools for solving industry's toughest multiphysics challenges. It also includes solutions for both direct and sequentially coupled physics problems including direct coupled-field elements [4].

In order to analyze the SRM by ANSYS Workbench, the geometrical model of the motor was plotted at first and appropriate materials are assigned to different regions [5]. The SRM has a complicated configuration and it is cumbersome and time-consuming to draw the geometrical model every time before simulation. This is not practical when the simulation model is supposed to be used in optimal design of the SRM where the design process should be repeated frequently. Therefore, a parametric geometric model is desirable [2,3].

With a reasonable approximate, the whole geometric structure of SRM is generated by geometric parameters, including radius of different parts of the motor, stator and rotor pole arc lengths. The design procedure for SRM is referred from [6, 7]. The dimensional details of 100 W, 3200 rpm SRM with 6/4 pole configuration is shown in the Table 1. and the cross section is shown in Figure 1. The details of stator pole configuration of model 1 is shown in Figure 2 and Table 2 respectively. Similarly, for the proposed model (model 2) details are shown in Figure 3 and Table 3 [7, 8].



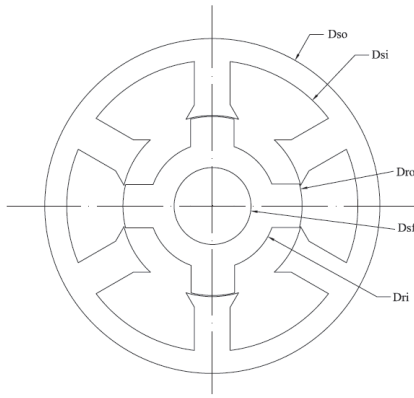


Figure 1. 6/4 Switched Reluctance Motor Geometry

Table 1: The Main Dimensions of SR Motor

Symbol	Meaning and Unit	Value
Dso	Stator outer diameter (mm)	122.0
Dsi	Stator inner diameter (mm)	106.0
Dro	Rotor outer diameter (mm)	65.4
Dri	Rotor inner diameter (mm)	46.0
Dsf	Shaft diameter (mm)	28.0
lg	Air gap (mm)	0.3
Lstk	Stack length (mm)	15.0
ns	Stator pole number	6
nr	Rotor pole number	4
q	Number of phase	3

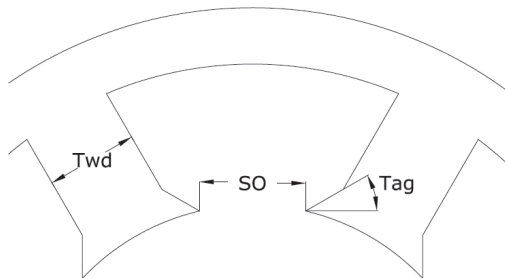


Figure 2. Stator Pole Configuration of Model 1

Table 2: Details of Stator Pole Shapes of Model 1

Symbol	Meaning and Unit	Value
Twd	Tooth Width (mm)	13
SO	Slot Open Length (mm)	15
Tag	Tooth Tang Angle (degree)	30

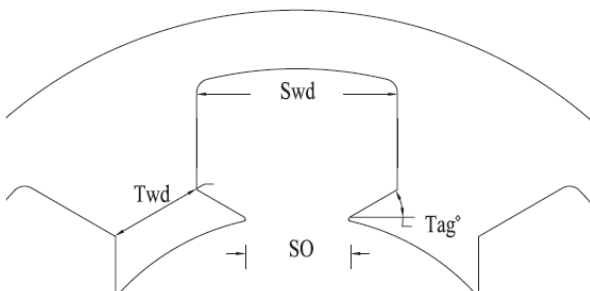


Figure 3. Stator Pole Configuration of Model 2

Table 3: Details of Stator Pole Shapes of Model 2

Symbol	Meaning and Unit	Value
Twd	Tooth Width (mm)	13
SO	Slot Open Length (mm)	15
Tag	Tooth Tang Angle (degree)	30
Swd	Slot Width (mm)	28

3. Finite Element Model

The magnetic field inside the motor is determined by computing the magnetic vector potential A . This satisfies the non-linear Poisson's equation.

$$\frac{\partial}{\partial x} \left(\gamma \frac{\partial A}{\partial x} \right) + \frac{\partial}{\partial y} \left(\gamma \frac{\partial A}{\partial y} \right) + \frac{\partial}{\partial z} \left(\gamma \frac{\partial A}{\partial z} \right) = -J \quad (1)$$

in a three-dimensional Cartesian system where γ is the magnetic reluctivity and J is the current density vector. The energy functional is a generalized form of a linear technique [8].

$$F = \int_V \int_0^B \bar{H} \cdot d\bar{B} dv - \int_V \int_0^A \bar{J} \cdot d\bar{A} dv \quad (2)$$

where B is magnetic flux density in Tesla (T), H is magnetic field intensity in Amps per meter (A/m), J is Current density in Amps per square meter (A/m²).

The 3D Finite Element Method (FEM) Analysis of SR motor is carried out with help of ANSYS workbench with the following assumptions

1. The current density within any conductor is uniform.
2. Hysteresis effects are neglected.
3. The induced conduction current in iron is neglected because of the relatively high resistance offered by steel laminations for eddy currents in the axial direction.

The simulation and experimental investigations of the electromagnetic field distribution of SR motor are analyzed with help of what-if analysis for different rotor positions for the given excitation current.

Torque characteristic is one of the most important electromagnetic characteristics of SRM, which can be used in calculation of average torque and torque ripple.[9,10] In fact, this static characteristic shows torque exerting on the rotor for different rotor positions. Direct calculation of torque in SRM with analytical method is impossible. Usually, torque is derived from the flux-linkage characteristic of phase winding. However, analytical methods cannot model precisely the region in where the stator and rotor poles begin to overlap, so prediction of the static torque is faced with a problem in this region [10,12-14].

Using ANSYS Workbench, it is possible to predict the torque directly. It is just enough to exert Maxwell work torque boundary conditions on the rotor [3].

4. Results and Discussion

- The variation of inductance for various rotor positions is shown in Figure.4. For model 2 it is found that in aligned position the variation of self inductance is minimum.
- The flux density variation for the both model is shown in Figure.5. In the model 2 variation of flux density is found less, will give more torque.



- Comparison of Figure. 7 and Figure. 8 gives the result of improvement of total force on rotor in model 2.
- The variation of directional force/torque along the X axis is shown in Figure. 9 and Figure. 10 it indicates that model 2 will give more torque than model 1.
- The Directional force/torque along y-axis from Figure. 11 and Figure. 12 can be found more in model-2.
- The flux density variation along motor body for both models is shown in Figure. 13 and Figure. 14. in model 2 it is clear that 'B' is increased.

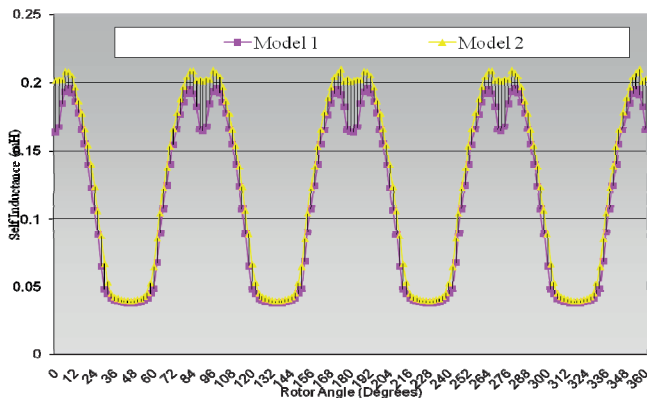


Figure 4. Self Inductance of winding at various Rotor positions

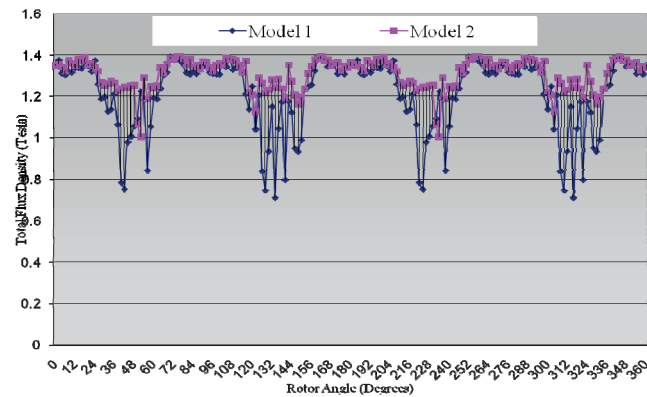


Figure 5. Flux Density Comparison at various Rotor positions

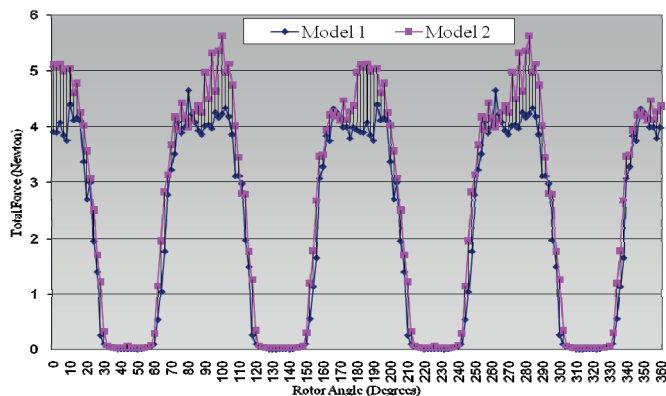


Figure 6. Total force Comparison at various rotor positions

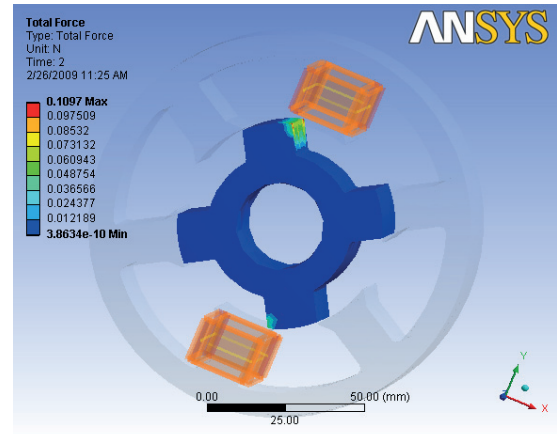


Figure 7. Total Force in Rotor for Model 1

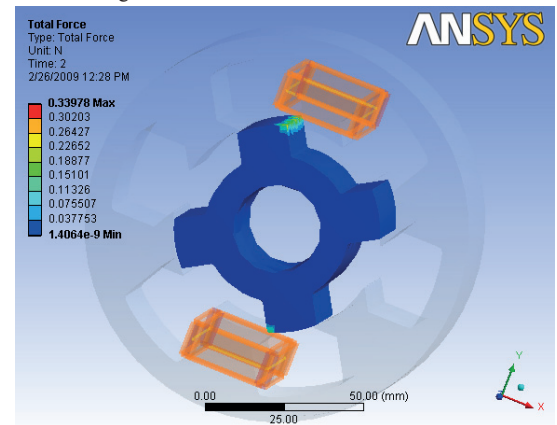


Figure 8. Total Force in Rotor for Model 2

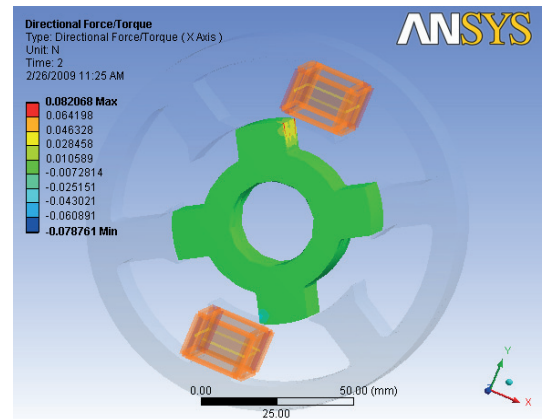


Figure 9. Directional Force/Torque along X-axis in Rotor for Model 1

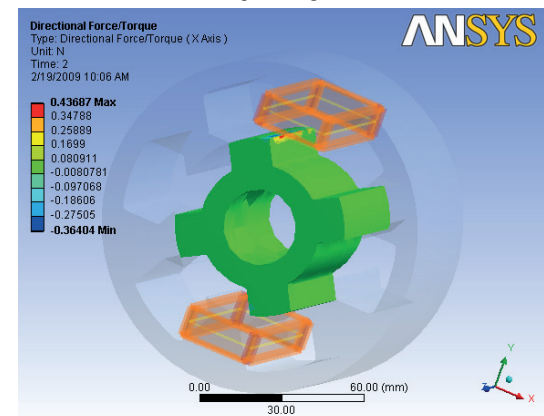


Figure 10. Directional Force/Torque along X-axis in Rotor for model 2



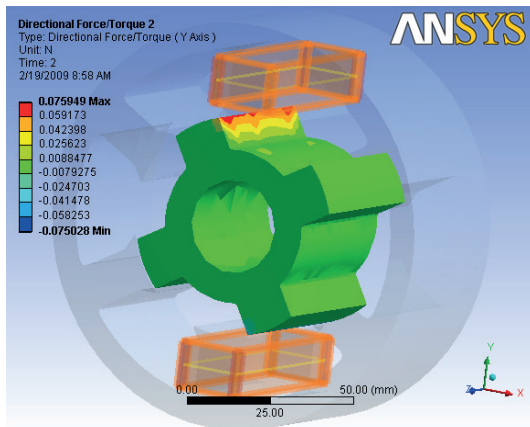


Figure 11. Directional Force/Torque along Y-axis in Rotor for model 1

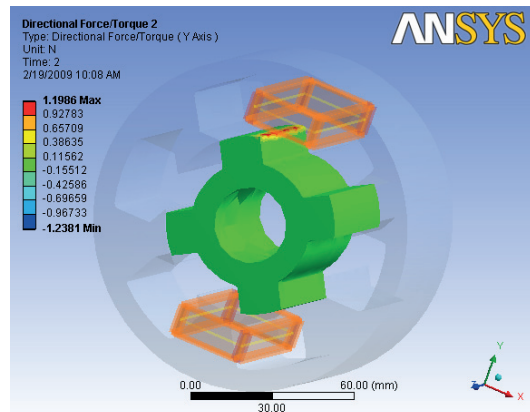


Figure 12. Directional Force/Torque along Y-axis in Rotor for Model 2

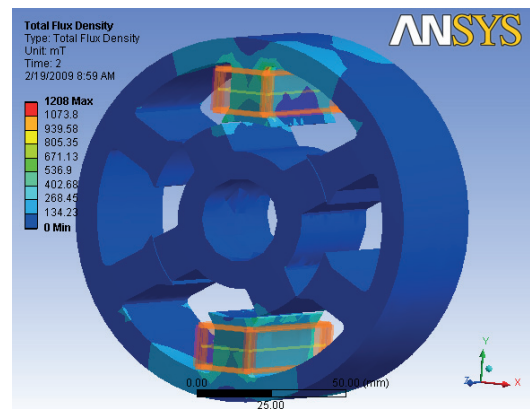


Figure 13. Variation of Flux Density for Model 1

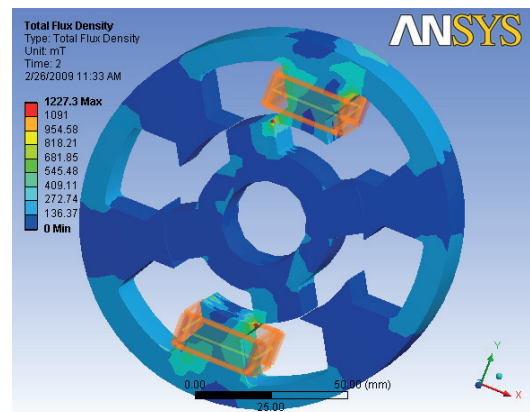


Figure 14. Variation of Flux Density for Model 2

5. Conclusion

In this paper three-dimensional magnetic analysis of a Switched Reluctance Motor with two different pole configurations have been given. From the analysis the variation of inductance, flux density & directional force / torque of both the model have been predicted. The results shows that the proposed pole configuration (model 2) is advantageous than the existing pole configuration (model 1). This study can be used for further modification of physical size of the motor to get more improved performance and to manufacture the SRM. In future the optimum shape and dimensions of SRM stator and rotor pole can be identified using soft computing techniques.

6. References

- [1] Ahmet Fenercioglu and Unal Kurt. Three Dimensional Magnetostatic Analysis of a 3-Phase, 12/8 Pole 250 W Switched Reluctance Motor used in a Washing Machine Drive, ELECO'2008 Elektrik - Elektronik - Bilgisayar Mühendisliği Sempozyumu Ve Fuarı.
- [2] Yusuf Oner and Ahmet Altintas. Computer Aided Design and 3D Magnetostatic Analysis of a Permanent Magnet Spherical Motor, Journal of Applied Sciences 7(22):3400-3409, 2007.
- [3] J. Faiz, B. Ganji, R. W. De Doncker, J. O. Fiedler. Electromagnetic Modeling of Switched Reluctance Motor Using Finite Element Method, IEEE Industrial Electronics, IECON 2006 - 32nd Annual Conference on Volume, Issue, 6-10 Nov. 2006 Page(s):1557 – 1562.
- [4] ANSYS Magnetic Valve Assembly demonstration example, a courtesy of INVENSYS [Online], Available: <http://www.ansys.com/demoroom/>
- [5] Mohamed Zribi and Muthana T. Alrifai. Robust Controllers for Variable Reluctance Motors, Hindawi Publishing Corporation, Mathematical Problems in Engineering 2005:2 (2005) 195–214.
- [6] R. Krishnan. Switched Reluctance Motor Drivers, Modelling, Simulation, Analysis, Design, and Applications, CRC Press, Boca Raton, London, 2001.
- [7] R. Krishnan, R. Arumugam and James F. Lindsay. Design Procedure for Switched-Reluctance Motors, IEEE Transactions on Industry Applications, Vol. 24, No. 3, May/June 1988
- [8] T. S. Low, H. Lin and S. X. Chen. Analysis and Comparison of Switched Reluctance Motors with Different Physical Sizes Using a 2D Finite Element Method, IEEE Transactions on Magnetics, Vol. 31, No. 6, November 1995.
- [9] R. Arumugam, D.A. Lowther, R. Krishnan, J.F. Lindsay. Magnetic Field Analysis of A Switched Reluctance Motor Using a Two Dimensional Finite Element Model, IEEE Transactions on Magnetics, Vol. Mag-21, No. 5, September 1985.
- [10] N. K. Sheth and K. R. Rajagopal. Torque Profiles of a Switched Reluctance Motor Having Special Pole Face Shapes and Asymmetric Stator Poles, IEEE Transactions on Magnetics, Vol. 40, No. 4, July 2004.
- [11] X. D. Xue, K. W. E. Cheng and S. L. Ho. A Self-Training Numerical Method to Calculate the Magnetic Characteristics for Switched Reluctance Motor Drives, IEEE Transactions on Magnetics, Vol. 40, No. 2, March 2004.



- [12] G. Henneberger , P h. K. Sat tler and D. Shen. Force Calculation with Analytical Accuracy in the Finite Element Based Computational Magnetostatics, IEEE Transactions on Magnetics, Vol. 27, No. 5, September 1991.
- [13] Stepen Hsien-Yuan Li, Feng Liang, Yifan Zhao and Thomas A. Lipo. A Doubly Salient Doubly Excited Variable Reluctance Motor, IEEE Transactions on Industry Applications Vol. 31, No. 1 January/ February 1995.
- [14] Wendy L. Lorimer, Dennis K. Lieu, John R. Hull, Thomas M. Mulcahy, and Thomas D. Rossing. Correlation of Experimental Data and Three-Dimensional Finite Element Modeling of a Spinning Magnet Array, IEEE Transactions on Magnetics, Vol. 30, No. 5, September 1994.



Mr. M. Sundaram received the BE and ME degree from Bharathiar University in 1997 and 2003. He is currently working as Senior Lecturer in PSG College of Technology, Coimbatore. His Professional and research interests in Switched Reluctance Motor.



Dr. P. Navaneethan received the BE degree from University of Madras in 1981 and ME degree from Anna University in 1983 and PhD from Indian Institute of Science, Bangalore in 1991. He is currently working as Professor & HoD of Electrical And Electronics Engineering Department, PSG College of Technology. He had presented about 15 International and National conference papers.



Mr. M. Vasanthakumar received the BE degree from the Anna University in 2006. He is currently doing Master Degree in Electrical Machines in the Department of Electrical and Electronics Engineering, PSG College of Technology, Coimbatore.

